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Abstract

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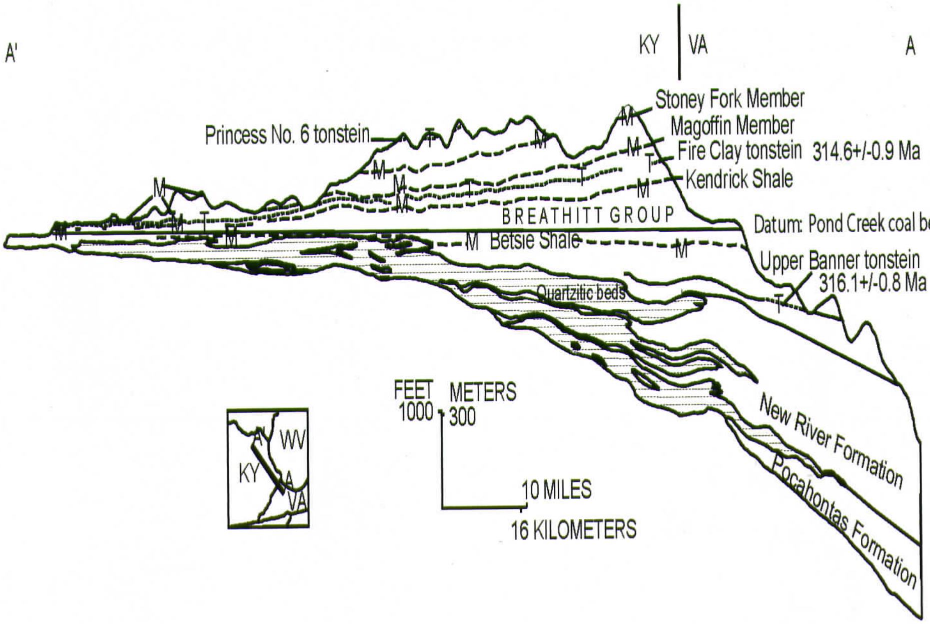

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AGE RELATIONSHIPS BASED ON SINGLE CRYSTAL ZIRCON U/PB AGES, PENNSYLVANIAN, CENTRAL APPALACHIAN BASIN, EASTERN KENTUCKY, USA

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ABSTRACT

High precision single crystal zircon U/Pb ages have been established for significant stratigraphic boundaries in the Pennsylvanian and beds within the Pennsylvanian. Using those ages and stratigraphic information derived from drill cores and detailed geologic mapping, it is possible to calculate net accumulation rates (NARs) from the thickness of the sediment column divided by the time interval spanned by the U/Pb ages and expressed as meters or feet per Ma and their distribution over wide areas. With paleontologic species and range distribution, the data also can help define climatic change events in the Pennsylvanian of the Appalachian Basin and possibly worldwide.

INTRODUCTION

High precision single crystal zircon U/Pb ages show that the time interval between the Upper Banner tonstein (316.1 ± 0.8 Ma) (Lyons et al., 1997) and the Fire Clay tonstein (314.6 ± 0.9) (Lyons et al., 2006) is 1.5 million years. Both the Upper Banner (Elswick) and the Fire Clay coal beds occur in the Majestic-Hurley-Wharncliffe Quadrangle, (MHW) Pike County, Kentucky (Outerbridge, 1968). The Pond Creek coal bed lies half way between the two. By interpolation, the age of the Pond Creek coal bed is 315.4 Ma. This study shows that numerical ages can be derived for beds in the Pennsylvanian of the central Appalachian basin by interpolation between U/Pb zircon ages derived from the Upper Banner (Elswick) and the Fire Clay tonsteins. The U/Pb zircon ages can be combined with similar ages from Gradstein et al. (2004) and Ogg (2007) to provide a framework on which to place paleontologic data and to calculate net accumulation rates for the units they bracket.

Stratigraphy

The Pennsylvanian beds of the central Appalachian basin are a complex assemblage of rock types that intergrade, interfinger, and fill channels eroded into older beds. They have been described at length by Wanless (1939) Morse (1931), Huddle and Englund (1966), and Huddle et al., (1963), and beds of the Breathitt Group have been mapped at 1:24,000 scale (Outerbridge, 1963, 1964; Rice, 1963, for instance).

Coal is the most important economic mineral deposit in the Pennsylvanian rocks of eastern Kentucky. It is widespread throughout eastern Kentucky from the base of the Breathitt Group to the top of the Pennsylvanian in Kentucky. It is extensively mined, and it supports the economy of eastern Kentucky. Excavations and core drilling for coal as well as for highways have provided much of the stratigraphic data for the geologic mapping of eastern Kentucky.

Certain coal beds in the central Appalachian basin, such as the Pond Creek coal bed, are widespread and easily recognizable. In particular, the Upper Banner, Williamson, Little Fire Clay, and Fire Clay coal beds commonly contain widespread tonsteins, and the Williamson, Taylor, and Broas coal beds are associated with the Kendrick, Magoffin, and Stoney Fork marine units, respectively, and are intensively used in correlations.

Flint clay is a general term for a clay that breaks into sharp edged lumps. Three general types of flint clay are distinguished: soft, composed primarily of illite, kaolinite, and some mixed layer clay; semi flint, composed of kaolinite, illite and a trace of mixed layer clay; and flint, composed of kaolinite and a little micrograined quartz (Stout et al., 1931; Patterson and Hosterman, 1962; Brown, 1978). Tonsteins are a subset of flint clay, because they break like flint clay and have much the same bulk composition. Phenocrysts of β-form quartz, sanidine, and euhedral zircon prove tonstein's volcanic origin but also admit exceptions to the general clay bulk composition. The tonstein of the Upper Banner coal bed, for instance, is rich in kaolinite crystals, β-form quartz, sanidine, and zircon and has a tar matrix, which is soluble in dimethylsulfoxide (DMSO).

Much of the flint clay in Kentucky is light gray to almost white. In some localities medium gray beds occur in the flint clay deposits. Where the gray beds have been sampled as tonsteins, they have proved to be tonsteins. Tonsteins that occur in or near coal beds are generally gray to black.

Tonsteins occur in at least 11 stratigraphic levels in Kentucky, Virginia, Ohio, and West Virginia. The Lower Banner tonstein was described in detail by Giles (1934), but he did not recognize it as a tonstein. Nelson (1959) was the first to recognize a volcanic ash in the Pennsylvanian of the Appalachians, just below the Pardee coal bed in Wise County, Virginia. Seiders (1965) proved the volcanic origin of the Fire Clay tonstein. Flint clays have also been reported in the Conemaugh and Monongahela (Windolph, 1987); some of these might be tonsteins.

Within the Appalachian basin the Vanport limestone is a marine unit that is as much as 2 m thick in northeastern Kentucky yet reaches 12 m in western Pennsylvania. In the Dingus Quadrangle (Outerbridge, 1978) of eastern Kentucky it is closely associated with an ash fall that has altered to a tonstein. During alteration, silica was released and was the likely source of the chert that is sporadically abundant at and above the limestone.

Above the chert and tonstein is a shale interval that locally occupies the whole interval from the Vanport Limestone to the Princess No. 6 (Lower Kittanning) coal bed. It is generally interbedded with thin coal beds (the Lawrence coal beds) and the Lawrence clay, a distinctive interval that includes numerous bodies of refractory flint and aluminous plastic and siliceous plastic clay (Stout et al., 1931), suggesting subaerial exposure and severe weathering over a long time. At least five tonsteins, datable by zircon U/Pb methods and correlatable by the distinctive trace element chemistry of the glass inclusions found in their β-form quartz crystals (Congdon et al., 1992; Webster et al., 1995) occur between the Vanport Limestone and the Princess No. 6 (Lower Kittanning) coal bed.

In general, any flint clay in the central Appalachian basin should be analyzed as a possible tonstein. The clay can be washed out of the sample after a two week or so soak in DMSO if it is a semi flint clay or, if the clay is a flint clay, with dilute hydrofluoric acid in about 15 minutes. The presence of euhedral β-form quartz, sanidine, and zircon is diagnostic.

Deposition-erosion, compaction vs. lithology

Deposition of the sediments that formed the Breathitt Group proceeded concurrently with but clearly exceeded erosion. What remains is the net accumulation. Evidence for erosion is found in channels eroded in earlier deposits and filled with sand and gravel. Compaction followed deposition, and observation of outcrops shows that sandstone and conglomerate locally contain fossil trees in growth position. Calcitic concretions and limestone are not compacted, as shown by unbroken shells and exoskeletons, siltstone is compacted to about half its original thickness, as shown by the draping of siltstone around calcite concretions, and shale is compacted to about a third or more of its original thickness, although it commonly contains undeformed marine fossils. Estimates of the compression ratios of coal beds vary widely.

Structure

Pennsylvanian rocks of the central Appalachian basin form a wedge, thickest on the southeast side of the basin (Figure 3), as discussed by Englund and Thomas (1990). The wedge shape reflects both the change in rate of sinking across the basin and the change in the rate of deposition across the basin (Cecil et al., 1985). Intervals between through going beds decrease northwestward but vary widely and apparently randomly so that beds 20 meters apart in one part of a quadrangle, for instance, may be only 3 meters apart in other parts of the same quadrangle, as shown in most geologic quadrangle maps in eastern Kentucky. Dips are very gentle, commonly of the order of 10 meters per kilometer, except near the few faults in the region. Most of the quadrangles mapped in eastern Kentucky are mapped without indications of faults near the surface. A master set of joints extends NW and NE and can be found wherever streams flow on bedrock. Stress relief joints are exposed along secondary highways throughout the region, run roughly parallel to the highways and to the hill slopes, and function as groundwater conduits to horizontal stress relief joints in the valley bottoms (Outerbridge, 1987).

U/Pb ages and the stratigraphic column

Derivation of Net Accumulation Rates

The availability of two high precision single crystal zircon U/Pb ages at two well- separated stratigraphic levels immediately suggested that the section between them could be dated. Extensive detailed mapping had already shown that the changes in thickness of the Kendrick marine zone-Fire Clay coal bed-Magoffin marine zone could be used to predict the stratigraphic interval between beds above and below that interval (Englund and Thomas, 1990).

The map of the MHW Quadrangle (Outerbridge, 1968), in which the stratigraphic section is scaled at one inch = 60 feet, is the only quadrangle map that depicts both the Elswick (Upper Banner) coal (316.1 ± 0.8 Ma) (Lyons et al., 1997) and the Fire Clay coal (314.6 ± 0.9 Ma) (Lyons et al., 2006) (Fig. 1). That section was used to fix by interpolation the age of the Pond Creek coal bed (Fig. 1) on the assumption that the net accumulation rate (NAR) was the same from the Elswick (Upper Banner) tonstein to the Fire Clay tonstein. The stratigraphic interval from the Fireclay coal bed to the Elswick (Upper Banner) coal bed is 430.5 m (Figure 1). The time interval between the two coal beds, based on the tonstein ages, is 1.5 Ma. The NAR for that interval is

$$430.5 \text{ m} \div 1.5 \text{ Ma} = 287 \text{ m/Ma}.$$

The stratigraphic interval between the Pond Creek coal bed and the Fire Clay coal bed in the same section is 213 m; therefore,

$$213 \text{ m} \div 287 \text{ m/Ma} = 0.742 \text{ Ma}.$$

The indicated age of the Pond Creek coal bed, then, is

$$314.6 \text{ Ma} + 0.742 \text{ Ma} = 315.342 \text{ Ma}.$$

The interval from the Elswick coal bed to the Pond Creek coal bed is 217.5 m;

Therefore,

$$217.5 \text{ m} \div 287 \text{ m/Ma} = 0.758 \text{ Ma}$$

And the indicated age of the Pond Creek coal bed is

$$316.1 \text{ Ma} - 0.758 \text{ Ma} = 315.342 \text{ Ma}.$$

which rounds to 315.3 Ma (Figure 1).

Once the age of the Pond Creek coal bed was set, the ages of other coal beds and marine zones could be extrapolated. Figure 1 shows the calculated ages of well-correlated beds (Englund and Thomas, 1990) in several drill cores in eastern Kentucky and southeastern Ohio. Data from Ogg (2007) allow the extension of age assignments above the Princess No. 9 (Upper Forepart) coal bed and below the Upper Banner (Elswick) tonstein. For the time being, the interval between the base of the Conemaugh Formation and the base of the Monongahela Formation may be interpolated using the data from Gradstein et al. (2004).

Eble (1994) and Wagner and Lyons (1997) both report a break in fossil sequences at the Upper Freeport coal bed. Wagner and Lyons (1997) report that the hiatus extends to near the top of the Conemaugh Formation.

Englund and Thomas section

Englund and Thomas (1990) (Figure 3) plot-

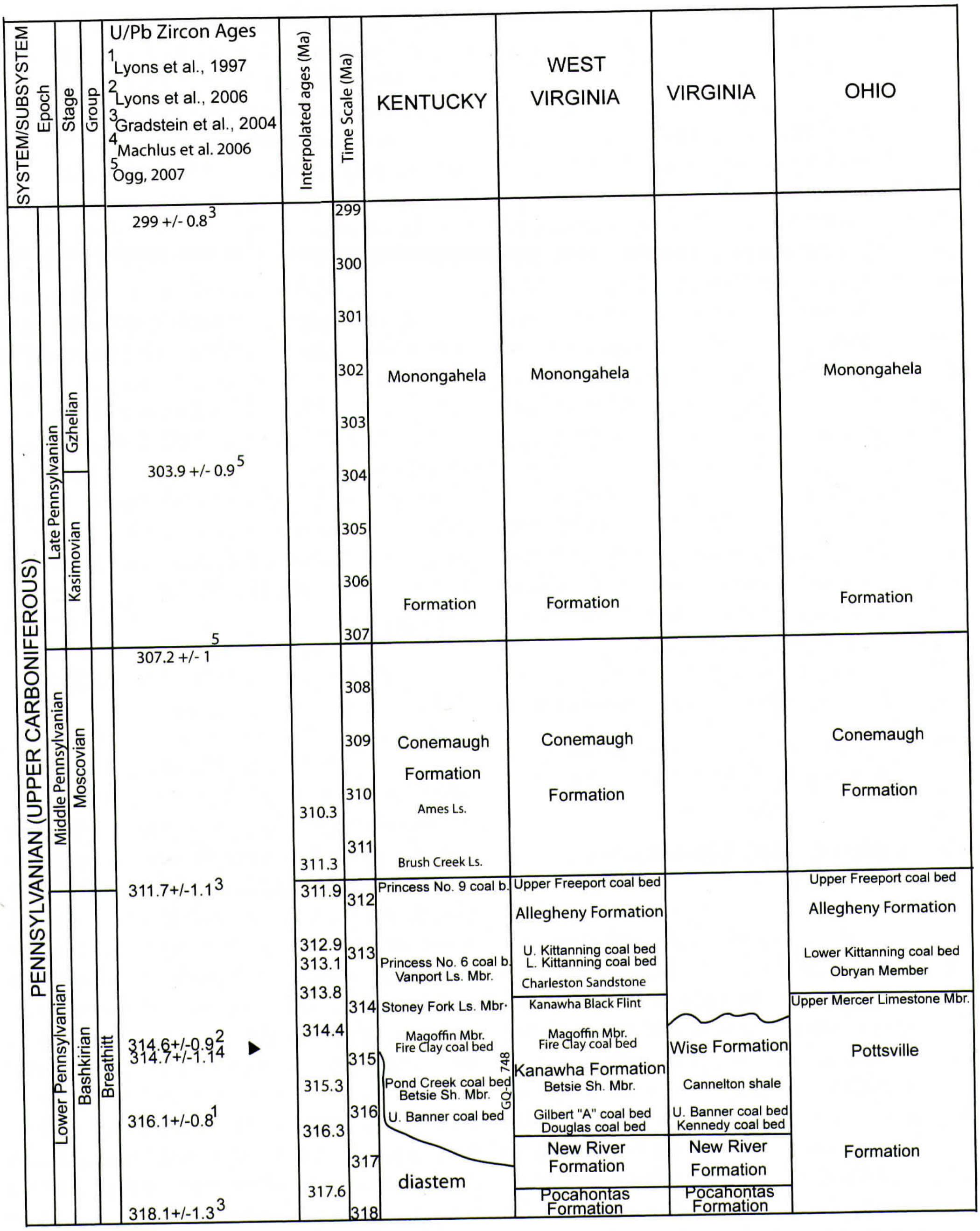

Figure 1. U/Pb zircon ages of stratigraphic units in the central Appalachian basin, Kentucky, West Virginia, Virginia, and Ohio. Mbr. means member, Ls means Limestone, GQ-748 marks the extent of the interval exposed in the geologic map of the MHW Quadrangle.

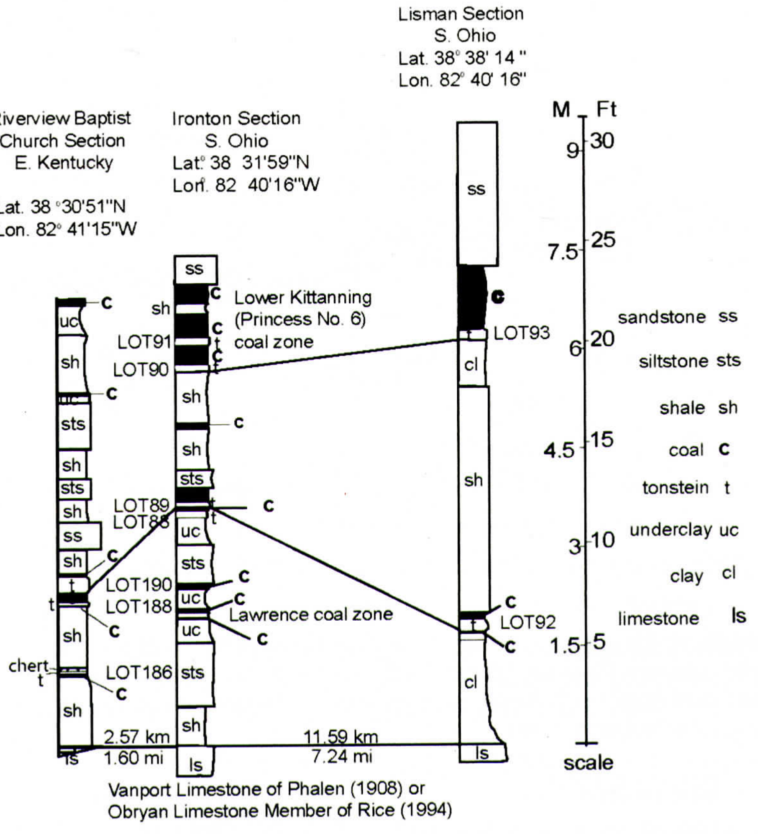

Figure 2. Measured sections of the interval between the Vanport Limestone of Phalen (1908) (Obryan Limestone of Rice, 1994) and the Princess No. 6 (Lower Kittanning) coal bed. Measured and sampled by Lyons, Outerbridge, and Triplehorn (indicated by LOT and sample numbers), correlations by glass inclusion chemistry (Congdon et al, 1992; Webster et al., 1995).

ted the stratigraphy along a line of closely spaced drill holes and measured sections across the central Appalachian basin and presented them in a cross section. Englund and Thomas's (1990) datum is the Pond Creek coal bed, which is present throughout the line of section (Figure 3). The thicknesses of the stratigraphic intervals between the Upper Banner tonstein, in the southeastern part of the section, and the Fire Clay tonstein, throughout the section, both referenced to the Pond Creek datum, were examined to see whether the whole Breathitt Group could be considered a homogeneous unit with respect to sediment accumulation rates (Outerbridge, 2006). A net accumulation rate (NAR) curve was determined that could be expressed by the equation:

$$\mathbf{y = 944 - 171 \ln x},$$

in which **x** is the distance in kilometers from the southeast side of the basin (the Tazewell-Buchanan County, Virginia, line) and **y** is the NAR in meters per million years (figure 4).

Extrapolation of ages above and below tonstein beds of known age is reasonable provided that the depositional style of the interval is the same from bottom to top. The calculated curve serves as a base line against which the dispersion of points in the measured curve can be tested. Points above the calculated curve reflect depositional rates in excess of what might be expected, and points below the calculated curve reflect depositional rates below what might be expected.

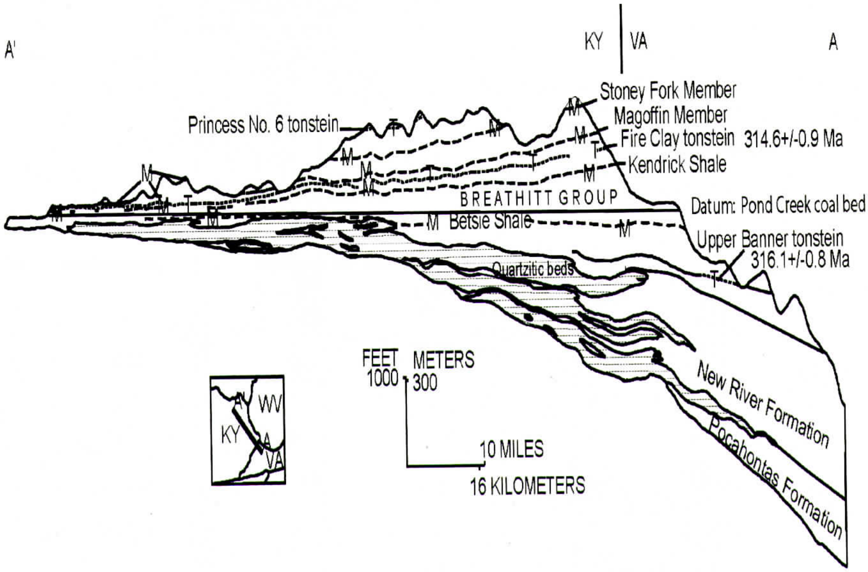

Figure 3. Stratigraphic cross section through part of the Pennsylvanian Breathitt Group in Kentucky and western Virginia. Marine beds are long dashed and marked M, tonsteins are short dashed and marked T. Stippled area predominantly quartzitic sandstone. Modified from Englund and Thomas, 1990.

DISCUSSION

Application of U/Pb ages

NAR contours

Examination of stratigraphic intervals from a set of diamond-drill core logs from scattered locations in eastern Kentucky and Ohio showed that the calculated ages of coal and marine beds interpolated between the Elswick (Upper Banner) and the Pond Creek coal beds and between the Pond Creek and the Fire Clay coal beds were consistent, but the thickness intervals varied widely because of differences in the NAR from place to place.

NARs were then calculated for beds cut in diamond drill cores in which two or more well-correlated and well-separated beds of known age are present in the core. The calculated and analyzed ages of the beds were consistent and the NARs varied systematically (figure 5).

Once NARs were calculated and their locations plotted on a map of eastern Kentucky, isolines were drawn that showed the change in rates of deposition across the easternmost area of the Breathitt Group. The map shows the decrease in NAR with distance from the present southeastern side of the central Appalachian Basin and reflects the approximate locations of sediment-laden streams as local extensions of higher NARs. In addition, since the depositional surface was close to sea level (Cecil et al., 1985), hence constant, the NARs also approximate the rate of sinking of the central Appalachian basin.

Calculated ages vs. relative ages

U/Pb zircon ages give precise (within a million years or so) ages to the bed from which the zircons were taken, and a set of such ages does so for the sequence in which these ages occur, but they cannot be extrapolated beyond the lithologies in which they occur. The condition of the zircons tends to rule out contamination from sidewalls of the volcanoes from which they came. The zircons are euhedral crystals as much as ten times as long as they are wide and show

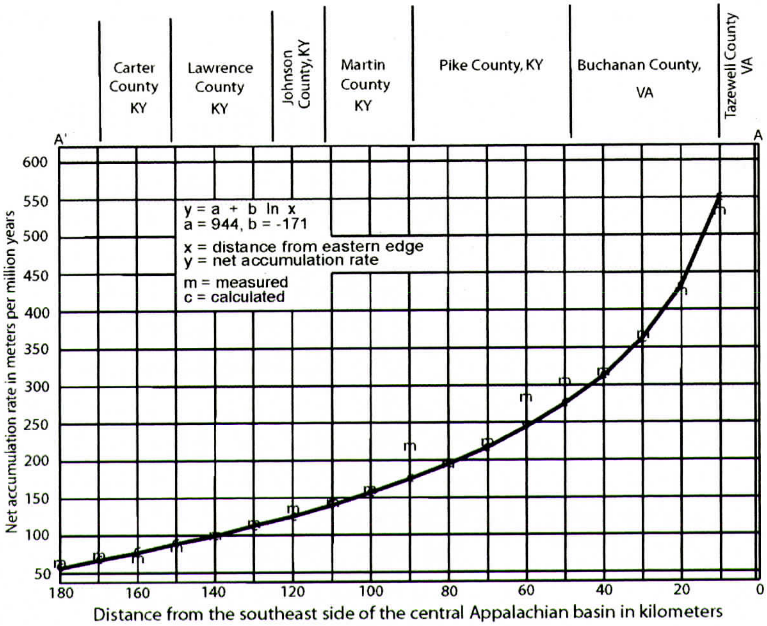

Figure 4. Regression curve and formula for the Early Pennsylvanian deposits in central Appalachian basin shown in Figure 3. Ordinate is on right side to match orientation of Fig. 3, measured intervals were measured from Englund and Thomas, 1990.

no sign of abrasion. The Breathitt Group and the Kanawha Formation, heterogeneous as they are, appear to be homogeneous in bulk. But where the depositional style changes, formation correlation stops.

Fossils, on the other hand, provide relative age information across lithologies as well as information on depositional environments. These types of information are complementary and can be combined once the age range of a fossil can be established.

For example, Gillespie and Pfefferkorn (1979) prepared a chart for the field trip through the proposed Pennsylvanian stratotype in West Virginia showing the stratigraphic distribution of common Pennsylvanian plant megafossils based on their relative ages. Eble (1994) noticed that several miospore species went extinct at about the level of the Allegheny - Conemaugh boundary (311.7 Ma). Wagner and Lyons (1997) concluded that a large stratigraphic gap exists at the base of the Upper Pennsylvanian Series that they attribute to a drying of the climate. A redrawing of the Gillespie and Pfefferkorn (1979) chart with modifications from Wagner and Lyons (1997) of the palynomorph names and with time as determined from single crystal zircon U/Pb age data in the ordinate (figure 6) provides confirmation of Wagner and Lyons' (1997) conclusion and a tighter control on the age and duration of the event. The chart shows that five species went extinct at or near the base of the Conemaugh, one started in the Conemaugh interval, four started near the Conemaugh-Monongahela boundary, and nine persisted through the Upper Pennsylvanian. The progression of species shown in the Gillespie and Pfefferkorn (1979) chart is shown as a fairly steady progression through time with a break at the base of the Conemaugh Formation (312 Ma) and a generous allowance of time for deposition of the very thick Pocahontas and New River Formations. The thickness of the Pocahontas and New River Formations (883 m in the Jewel Ridge Quadrangle (Englund, 1981) for example) and the abundance of the coal beds led to the impression that it took a long time to deposit those units. In the present chart the New River Formation was deposited during an interval of about 0.4 Ma, the Pocahontas Formation

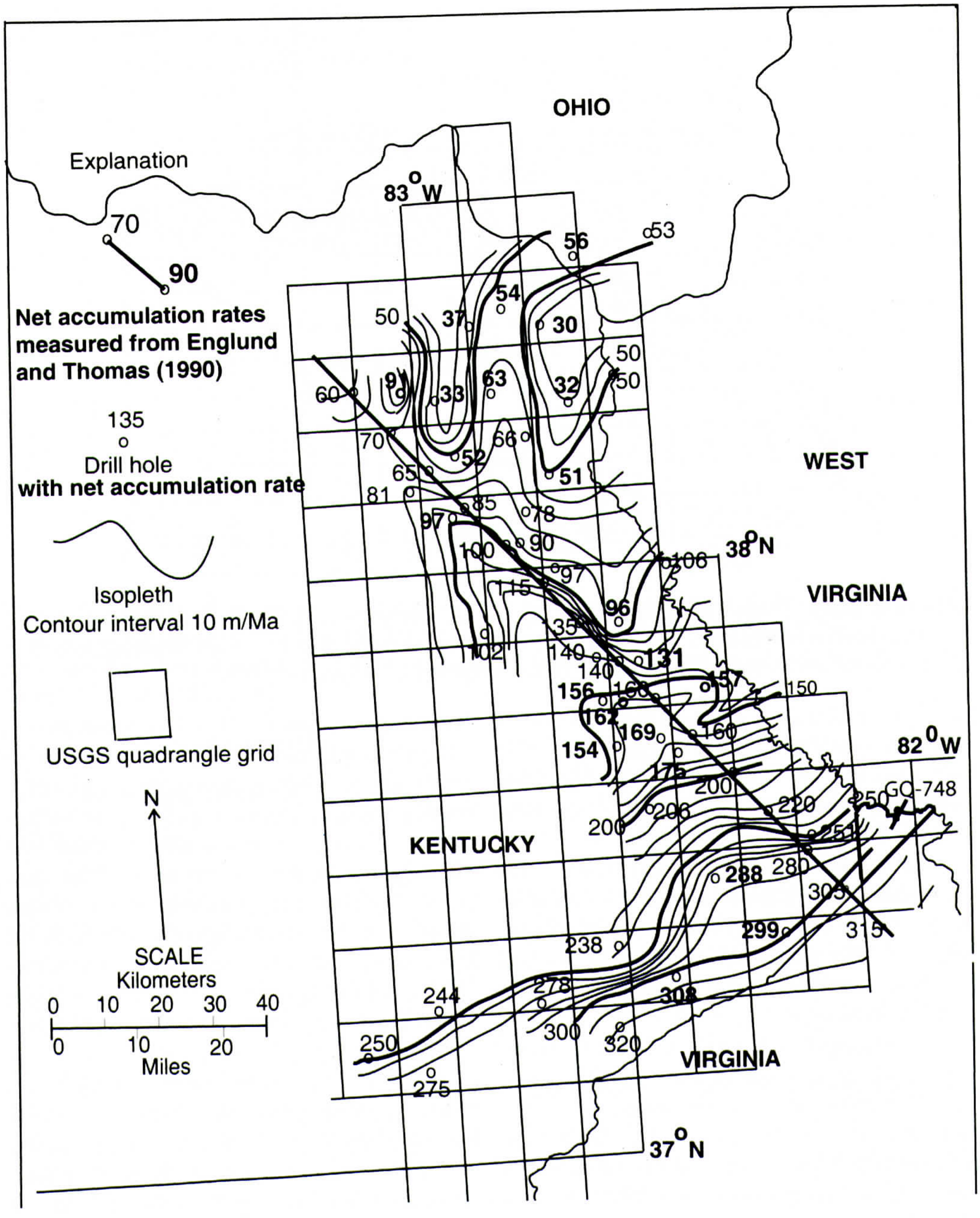

Figure 5. Distribution of net accumulation rates (in meters per million years) in the Breathitt Group of easternmost Kentucky and equivalent strata in Ohio.

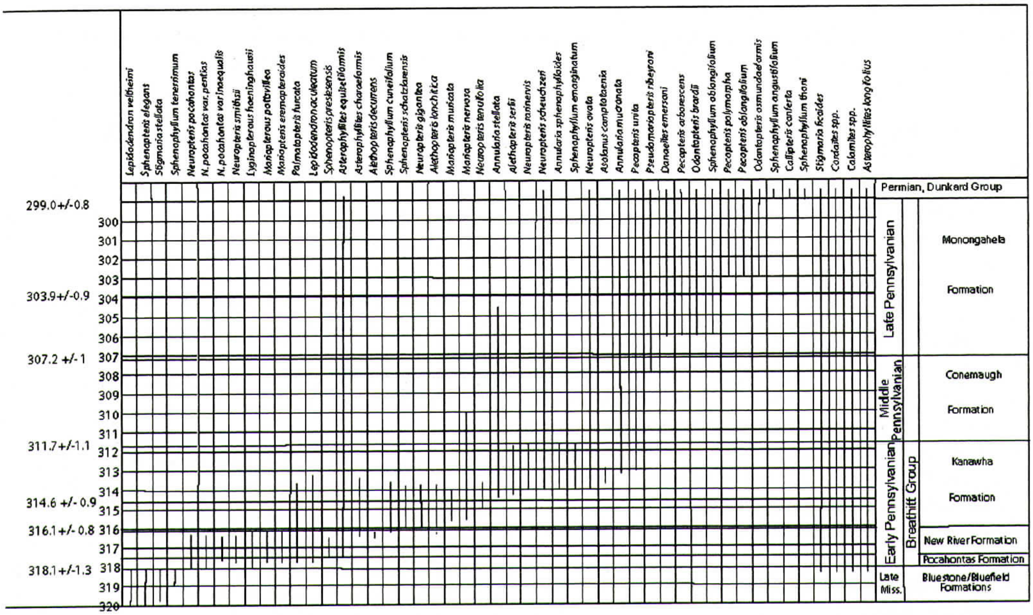

Figure 6. Ranges in time of some plant megafossils in the central Appalachian basin. Modified from Gillespie and Pfefferkorn (1979).

during an interval of about 1.3 Ma, the Kanawha Formation about 2.5 Ma, the Allegheny Formation about 2.8 Ma, the Conemaugh Formation about 4 Ma, and the Monongahela Formation about 8 Ma.

CONCLUSIONS

Sandstone and siltstone are by far the dominant rock types in the central Appalachian basin. Deposition was in deltas, always at or very close to sea level, so the NARs reflect the rate of subsidence for the interval measured at the point of measurement.

Figure 5 shows the distribution of a set of NARs measured on diamond-drill cores in the stratigraphic interval of the Breathitt Group of Kentucky. The contours also show the rate and distribution of subsidence of that part of the central Appalachian basin during deposition of the Breathitt Group.

Figure 6 shows that plant megafossils have short ranges and many forms in the Lower Pennsylvanian and can be useful in carrying time lines into other basins. In the Middle Pennsylvanian Conemaugh Formation, no short range plant megafossils have been reported, and the long range fossils are of little use in dating the Conemaugh. New forms of plant megafossils evolved at the beginning of the Monongahela Formation but extend through that formation and support an age of Monongahela and younger. Other forms, microfossils perhaps, might be used in correlations in the Middle and Upper Pennsylvanian. The Figure 6 template can be used with any set of Pennsylvanian fossils.

Tonsteins appear to be abundant in the Appalachian basin. Any flint clay observed in outcrop should be tested for phenocrysts. If euhedral zircons, β-form quartz crystals, and euhedral sanidine crystals are found, the flint clay is certainly a tonstein. Quartz shards, flakes, and blades, as well as kaolinite crystals (worms), are a strong indication that the claystone is a tonstein.

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A Soil Chronosequence Study on Terraces of the Catawba River near Charlotte, NC: Insights into the Long-term Evolution of a Major Atlantic Piedmont Drainage Basin

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ABSTRACT

Relatively few soil chronosequence or long-term landscape evolution studies exist for the Piedmont of the southeastern United States. Here, we present a chronosequence of soils on five well-expressed, unpaired alluvial terraces from the Catawba River near Charlotte, NC. Ten soil profiles were excavated and described on the terrace sequence. Soil pits were sampled by horizon and the <2 mm fraction analyzed for particle size and extractable iron. Ages are assigned to the terrace units through comparison with regional surface age/elevation curves (Mills, 2000). The elevations (and calculated ages) of the terraces above the modern channel are: 3 m (4±0.5 ka), 10 m (50±6 ka), 14 m (128±16 ka), 28 m (610±75 ka), 42 m (1,470±180 ka).

Color hue, pedogenic iron (Fe_d) and clay content (%) recorded positive trends with increasing terrace age. Specifically, these variables increased from 10YR to 2.5YR, 3.6% to 6.4%, and 21.9% to 62.6% respectively, from the lowest (~4 ka) to the highest (~1,470 ka) terrace. These results are consistent with regional chronosequence studies developed in different physiographic provinces and parent materials. This consistency implies that the relatively rapid oxidation of iron bearing minerals and development of pedogenic clays overshadows the effect of differences in parent material and regional climate. The rate of development of these soil properties plateaus after ~128 ka. Fe_o/Fe_d ratios and clay contents record a break in soil development between ~128 and 50 ka, which is ascribed to the inheritance of reworked, previously weathered material. These results indicate a unique, dramatic change in the sediment provenance of the Catawba River from the erosion of relatively unweathered bedrock to relatively well developed soils, stripped from basin hillslopes during this time period. This switch represents a major change in landscape evolution likely driven by the colder climatic conditions of the Late Pleistocene. Sedimentological changes from cobble gravel facies to sand facies indicates that terrace formation was coupled with a change in fluvial transport capacity prior to ~128 ka. These data represent some of the first insights into the long-term soil and landscape evolution of a major drainage in this region of the Piedmont.

INTRODUCTION

Despite their value in Quaternary geologic studies, relatively few soil chronosequences exist for the southeastern United States (Fig. 1). Soils develop under the influence of several environmental factors including climate, organisms, relief, parent material and time (Jenny, 1994). A soil chronosequence is defined as a series of soils for which weathering characteristics vary as a function of time. Using this paradigm, soil development can be employed as a tool for mapping, correlating and assigning ages to Quaternary deposits (e.g. Leigh, 1996; Mills, 2005), for understanding landscape dynamics in the context of climate change or tectonics (e.g. Eppes et al., 2002, 2008), or for evaluating ecosystem variability (e.g. McAuliffe et al., 2007). Previous chronosequence studies on fluvial terraces in the southeastern

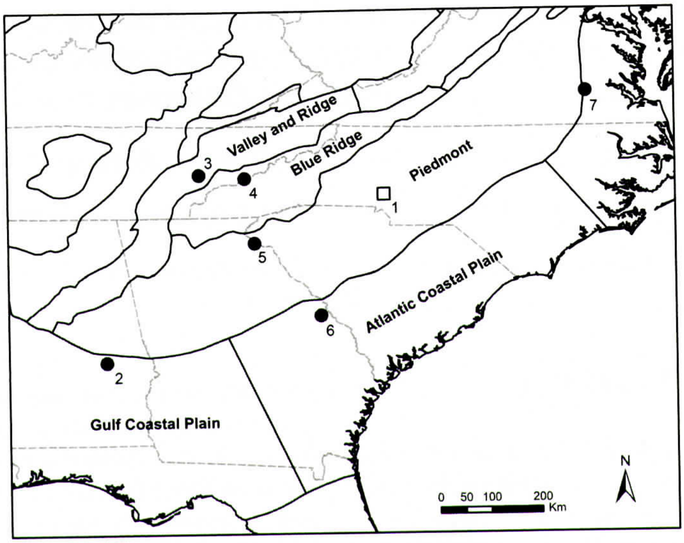

Fig.1. Map of select physiographic provinces in the southeastern United States. Figure shows approximate location of study area and published regional chronosequence studies as follows: 1) Study location; 2) Shaw et al. (2003); 3) Delcourt (1980); 4) Leigh (1996); 5) Foss et al. (1981); 6) Pavich et al. (1981); 7) Howard et al. (1993).

United States have been conducted in the physiographic provinces of the Valley and Ridge (e.g. Delcourt, 1980), Blue Ridge Mountains (e.g. Leigh, 1996), Piedmont (e.g. Foss et al., 1981) and Coastal Plain (e.g. Markewich et al., 1989; Howard et al., 1993; Shaw et al., 2003) (Fig. 1). More comprehensive chronosequences exist for the Coastal Plain due to terrace continuity and the availability of paleontologically dated marine units (Mills, 2005). Chronosequence studies on other deposits in this region, such as pediments, alluvial fans and debris flows, have typically focused on the Blue Ridge Mountains (e.g. Mills, 1983; Mills and Allison, 1995; Liebens and Schaetzl, 1997). The dearth of chronosequence studies in the Piedmont physiographic province is likely due to a number of factors including the overall maturity of the landscape and consequent perceived homogeneity of "red clay" soils, and the lack of exposure of a suitable stratigraphy of landforms. Nevertheless, such studies still stand to provide valuable insights into the landscape evolution of this understudied region.

The major drainages of the southeastern United States have also received little study in the Piedmont. Long-term fluvial evolution research in the eastern United States has tended to focus on more northern drainages or other physiographic provinces. For example, several studies have investigated terraces of the Susquehanna River to interpret the interaction of fluvial processes with base level fluctuations (isostatic and eustatic) and changes in climate (e.g. Pazzaglia and Gardener, 1993; Engel et al., 1996; Reusser et al., 2006). Research conducted on the alluvial deposits of the New River in the Valley and Ridge province of Virginia has documented late Cenozoic channel migration (e.g. Bartholomew and Mills, 1991), as well as the timing and rates of Quaternary incision and aggradation events (e.g. Granger et al., 1997; Ward et al., 2005). More recently, Leigh (2008), utilizing fluvial deposits in the Atlantic Coastal Plain, documented the fluvial response of river channels to Late Quaternary climate change. The depositional and incisional history of drainages in the southeastern Piedmont however is effectively unexplored despite the fact that the evolution of these major drainages could provide insight into ongoing landscape scale response to climate and land use change.

In this study, we aim to improve understand-

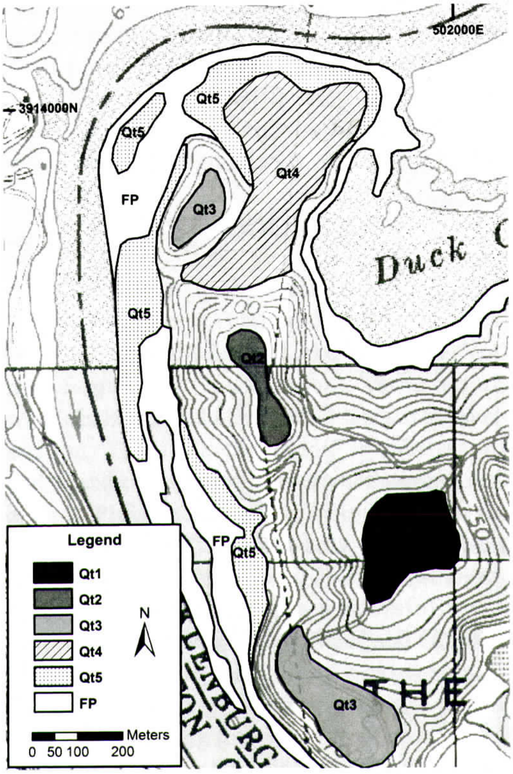

Fig.2. **Surficial geologic map of study area showing terrace tread(Qt1-5) and floodplain (FP) surfaces. Base map includes USGS 7.5' Quadrangles Mountain Island Lake and Lake Norman South. Contour interval is 10 feet.**

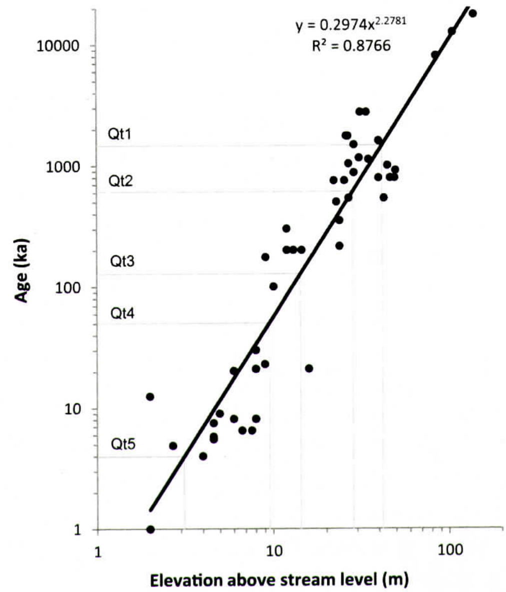

Fig.3. Log-log plot of surface age vs. elevation above modern stream level (modified from Mills, 2000). We estimate error on calculated ages for terrace units to be within 13% based on the unexplained variance.

ing of the soil geomorphology and landscape evolution of the Piedmont physiographic province in the southeastern United States through the study of fluvial terraces located in the Cowan's Ford Wildlife Preserve, NC. In this locality, an unusually large meander bend of the Catawba River has resulted in the preservation of a suite of terraces that have been relatively undisturbed by modern development. We describe the stratigraphy, sedimentology and soils of these terraces and in doing so provide insight into the long-term fluvial history of a major east coast drainage basin.

GEOLOGY AND SETTING

The study area is located along the Catawba River in the Cowen's Ford Wildlife Refuge, near Charlotte, in the Piedmont of North Carolina (Figs. 1 and 2). The Catawba River is approximately 350 km long and flows from the Blue Ridge Mountains to its confluence with the Wateree River in South Carolina. The Catawba River watershed drains approximately 9,000 km^2 of Western North Carolina. The modern channel is heavily impounded by seven reservoirs designed for hydroelectric power generation. The study area is located at the uppermost end of Mountain Island Lake, where the river is sometimes still free flowing. Soils in the area are mapped as Typic Hapludults (Cecil, Georgeville, and Pacolet Series), Rhodic Peludults (Davidson Series), and Fluvaquentic Eutrochrepts (Monacan Series). The study area lies within the Charlotte Belt, which consists of intrusive plutonic suites, ranging from gabbro to granitic rock, as well as metamorphosed diorite and biotite gneiss. Bedrock in the field area consists of metagranodiorite, comprised mainly of plagioclase, quartz, potassium feldspar, and biotite. The modern climate is characterized by hot, humid summers and moderate,

Table 1. Representative soil properties described from soil pits on terrace units.

Unit	Horizon	Depth	Color		Gravel	Texture	Structure	Consistence		Clay	Boundary	Roots	Pores
		(cm)	Moist	Dry	(%)			Wet	Moist	Films			
Qt1	Ap	0-21	5YR 3/4	5YR 4/6	<10	CL	3 m sbk	ss-s p	fi	3 p cobr	a s	2m 3f 3vf	1c 1m 1f 2vf
	Bt1	21-64	2.5YR 3/6	2.5YR 4/6	<10	L	3 m sbk	s p	fi	3 p cobr	d s	2m 1f 1vf	1m 3vf
	Bt2	64-105	2.5YR 3/6	2.5YR 4/6	<10	L	3 c sbk	s p	fi	3 p cobr	---	1m	3vf
Qt2	Ap	0-20	7.5YR 4/6	7.5YR 4/6	<10	SL	2 f sbk	so po	fr	---	c s	1m 3f 3vf	2f 3vf
	Bt1	20-73	2.5YR 4/8	2.5 YR 5/8	<10	C	3 f sbk	s p	fi	3 d pf	d s	3f 3vf	2f 3vf
	Bt2	73-128	2.5YR 3/8	2.5YR 5/8	<10	C	3 f sbk	s p	fi	3 p cobr	---	1m 2f 2vf	---
Qt3	Ap	0-10	7.5YR 2.5/3	7.5YR 3/3	<10	L	2 f sbk	ss p	fr	---	a s	2c 2m 2f 3vf	1c 3m 3vf
	Bt	10-25	5YR 3/3	5YR 4/3	<10	L	3 f abk	s p	fi	3 d cobr	c s	2c 2m 2f 2vf	2m 1f 3vf
	Btc1	25-45	5YR 4/4	5YR 4/4	<10	CL	3 f abk	s p	fi	3 p cobr	c s	1f 2vf	2m 3vf
	Btc2	45-102	2.5YR 4/6	2.5YR 4/6	<10	C	3 f abk	s p	fi-vfi	3 p cobr	---	1f 1vf	3vf
Qt4	Ap	0-20	7.5YR 5/6	7.5YR 5/6	<10	L	2 f sbk	ss p	fi	---	a s	1c 1m 2f 3vf	1c 1m 2f 3vf
	Bt1	20-52	5YR 5/8	5YR 5/6	<10	C	2 m sbk	s p	fi	3 p cobr	g s	1f 1vf	1f 3vf
	Bt2	52-77	5YR 5/8	5YR 5/6	<10	C	2 f sbk	s p	vfi	3 p cobr	---	---	1vf
Qt5	A	0-10	10YR 3/3	10YR 5/2	<10	SIL	3 f sbk	ss ps	fr	---	a s	1c 2m 2f 2vf	3m 2f 3vf
	Bc	10-21	10YR 3/6	10YR 5/4	<10	L	2 m sbk	s p	fr	---	a s	2c 2m 3f 3vf	1m 2f 3vf
	Btc1	21-39	10YR 5/6	10YR 6/4	<10	L	2 m sbk	s p	fr	2 d pf	g s	1f 1vf	1m 2f 3vf
	Btc2	39-55	10YR 5/8	10YR 6/6	<10	L	2 c sbk	s p	fi	2 d pf	c s	1m 1vf	1f 2vf
	Btc3	55-82	10YR 5/6	10YR 6/6	<10	L	2 m sbk	s p	fi	2 d pf	---	---	2vf

Subordinate horizons: c = manganese concretions, p = ploughed, t = clay accumulation
Texture: C = clay, CL = clay loam, SL = sandy loam, L = loam, SIL = silty loam.
Structure: Grade: 1 = few, 2 = common, 3 = many; Size: f = fine, m = medium, c = coarse; Type: abk = angular blocks, sbk = sub-angular blocks.
Consistence: so = non-sticky, po = non-plastic, ss = slightly sticky, ps = slightly plastic, s = sticky, p = plastic; fr = friable, fi = firm, vfi = very firm.
Clay films: 1 = few, 2 = common, 3 = many; d = distinct, p = prominent; pf = ped faces, co = coats, br = bridges.
Boundary: a = abrupt, c = clear, g = gradual, d = diffuse; s = smooth.
Roots and pores: Grade: 1 = few, 2 = common, 3 = many; Size: vf = very fine, f = fine, m = medium, c = coarse.

short winters. Annual precipitation averages approximately 106 cm, while average temperatures range from 5 °C in January to 25 °C in July (NOAA, 1981-2010). Vegetation consists primarily of mixed hardwood and pine-hardwood forests and grasslands.

METHODOLOGY

Terraces were mapped in the field utilizing topographic maps (United States Geological Survey Mountain Island Lake and Lake Norman South 7.5' Quadrangles). Terrace units were distinguished based on 1) terrace tread elevation, 2) soil development, 3) stratigraphy and 4) sedimentology. Numerical dating of older (e.g. Pleistocene) alluvial landforms in the Eastern United States has until recently been largely unobtainable (Mills, 2005). Cosmogenic isotope dating has been successfully employed in some studies (e.g. Mills and Granger, 2002) but remains prohibitively expensive. In this study, we assign numerical ages to terrace units by comparing the elevation of mapped terraces above the modern river channel to regional surface age/elevation curves published by Mills (2000; Fig. 3). Mills utilized data from research conducted throughout the southeastern and eastern United States and obtained a strong correlation between surface age and elevation above the modern stream channel (R^2 value of 0.877).

A total of ten soil profiles, two per terrace unit, were described according to Soil Survey Staff (1993) and Birkeland (1999). Soil pits were both hand excavated (5 total) and exhumed via auger boring (5 total). All profiles were located on relatively flat tread surfaces, away from terrace scarps in order to minimize the effects of erosional and colluvial processes. Analysis of soil morphology from soil pits (Table 1) included descriptions of horizon thickness and boundaries, color, structure, gravel content, consistence, roots and pores, texture, clay films, as well as sedimentary descriptions (grain size, rounding, sorting). Select properties were described from auger borings to account for spatial variability. Pits were sampled by horizon with multiple samples being collected where horizons were greater than 25 cm in thickness. All samples were sieved in the field and the <2 mm fraction analyzed for particle size (pipette method). Iron content was measured through both oxalate (McKeague and Day, 1966) and dithionite-citrate (Mehra and Jackson, 1960) methods for samples from horizons with the greatest evidence of weathering (B or Bt horizons).

RESULTS

Five distinct, unpaired terrace treads (Qt1-Qt5) were distinguished in the field area ranging from 3 to 42 m in elevation above the modern channel (Fig. 2). Soil morphological data described from soil pits for each terrace unit is provided in Table 1. The Qt1 terrace is the highest in the sequence standing approximately 42 m above the modern stream channel. The calculated age for the unit based on this elevation is 1,470±180 ka (Fig. 3). The unit is characterized by alluvial sediments, comprising pebble and cobble gravel, with moderately to poorly sorted, sub-rounded to rounded quartzite clasts. These clasts, varying in size from 4-60 mm, were distributed throughout the profile, with a clast supported facies beginning at a depth of 2.1 m below the tread surface. Qt1 soils exhibit Ap/Bt horizonation and are characterized by dark reddish brown to red colors (5YR 3/4 to 2.5YR 4/6) and sticky to plastic consistence. Soil texture consists of clay, which grades upward to clay loam. Soil structure is well developed with distinct sub-angular, blocky peds between 10-20 mm in diameter. Clay content in the soil varies from 31.9% in the A horizon to 61.9% in the B horizon (Fig. 4) with many, prominent clay films forming coats and bridges. Extractable iron content in the B horizon was determined to be 6.37% (Fe_d) and 0.61% (Fe_o) with an iron activity ratio (Fe_o/Fe_d) of 0.10 (Fig. 5).

The Qt2 terrace tread is approximately 28 m in elevation above the modern channel of the Catawba River and was assigned an age of 610±75 ka (Fig. 3). Several quartzite clasts, ranging in size from 2 to 50 mm, were distributed throughout the soil profile, suspended in a fine-grained matrix. Clast supported gravel and

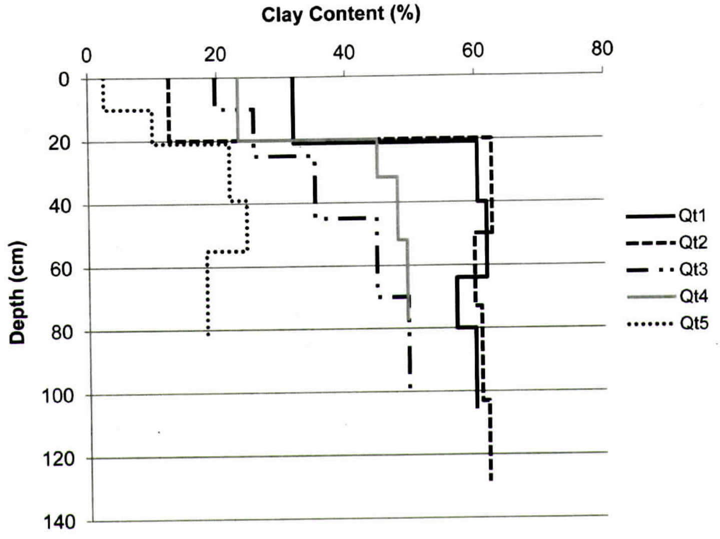

Fig. 4. Depth profile plot of clay content (%) for representative soil profiles on terrace units. Analytical error is <1% for clay content.

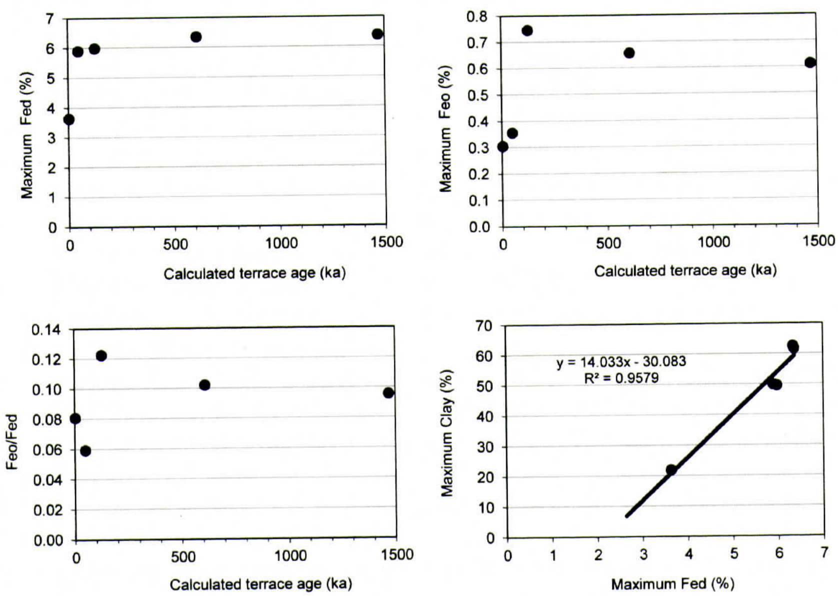

Fig.5. Chronofunctions of extractable iron for representative terrace soils. Plots show maximum extractable iron values (both Fe_d and Fe_o) from the B horizon, iron activity ratios (Fe_o/Fe_d) and the relationship between Fe_d and clay content (%). Analytical errors are <0.2% for Fe_d and Fe_o. Estimated ages for terrace units are: 4 ka (Qt5), 50 ka (Qt4), 128 ka (Qt3), 610 ka (Qt2), and 1,470 ka (Qt1).

cobble facies were found 1.3 m below the tread surface. Soil development is characterized by Ap/Bt horizonation with strong brown to red coloration (7.5YR 4/6 to 2.5YR 5/8), strongly developed structures with sub-angular blocky peds, between 5-10 mm in diameter, and sticky to plastic consistence. Soil texture consists of clay, which grades upward to silt loam. Qt2 soils have the highest observed clay content, which ranges between 59.8% and 62.6% in the B horizon (Fig. 4), and have many distinct to prominent clay films covering ped faces and forming bridges between peds. Iron contents were similar to Qt1 soils with values of 6.35% (Fe_d), 0.66% (Fe_o) and a Fe_o/Fe_d ratio of 0.10 (Fig. 5).

The Qt3 unit stands at a relative elevation of 14 m above the river and has a calculated age of 128±16 ka (Fig. 3). The alluvial parent material consists of moderately to well sorted gravelly sand, with approximately 10% quartzite pebble and cobble gravels, ranging from 5-20 mm in diameter. No gravel and cobble facies were found in this unit; rather an unweathered, well-sorted compacted sand layer was discovered at 2.4 m depth. Qt3 soils have A/Bt horizonation with manganese concretions in the B horizon, approximately 5 mm in size, below 25 cm in depth. Soil color ranges from dark brown (7.5YR 2.5/3) in the A horizon to red (2.5YR 4/6) in the B horizon. Soil consistence is sticky and plastic. Soils have clay textures, which grade upward to clay loams and loams, as well as strongly developed structures with angular blocky peds between 5 and 10 mm in diameter. Clay films are prominent in the B horizon forming coats and bridges; however measured clay content is less than that of Qt1 and Qt2 units ranging from 25.7% to 49.5% in the B horizon (Fig. 4). Qt3 soils recorded the highest Fe_o values of 0.75%. Fe_d values were 5.98%, which yielded the highest Fe_o/Fe_d ratio of 0.12 (Fig. 5).

Qt4 deposits stand approximately 10 m in elevation above the modern river channel. The calculated age for the unit based on this elevation is 50±6 ka (Fig. 3). The alluvial parent material is composed of well-sorted silty sand with less than 5% fine quartzite pebble gravel. Soil development is characterized by A/Bt horizonation with colors ranging between strong brown and yellowish red (7.5YR 5/6 – 5YR 5/8). A typical Qt4 soil has a sticky and plastic consistence, clay texture which grades upward to loam, and a moderately developed structure, with sub-angular peds primarily between 5 and 10 mm in diameter. The range of clay content in the B horizon, between 44.9% and 49.4% (Fig. 4), was typically higher than in Qt3 deposits, although the maximum measured clay content was similar. Peds were covered with prominent clay coatings, which formed coats and bridges. Extractable iron content was determined to be 5.90% (Fe_d) and 0.36% (Fe_o), which yielded the lowest Fe_o/Fe_d ratio of 0.06 (Fig. 5).

The lowest terrace unit (Qt5) sits 3 m above the modern channel and has a similar alluvial parent material composition to Qt3 and Qt4 deposits. The determined age for the unit based on this elevation is 4±0.5 ka (Fig. 3). Soil development is weakest in this unit typified by A/B/Bt horizonation, 10YR color hues (10YR 3/6 - 10YR 6/6), loam textures and relatively low clay contents (10.0% to 24.5% in the B horizon) (Table 1; Fig. 4). Qt5 soils also had the lowest extractable iron content. Fe_d was measured at 3.63%, Fe_o 0.31%, and Fe_o/Fe_d 0.08 (Fig. 5). Soil consistence was similar to other units (sticky and plastic) while structure was moderately developed with sub-angular peds between 10 and 20 mm. Manganese nodules between 2 and 8 mm in diameter were noted in all B horizons.

DISCUSSION

Soil Chronosequence

Soil morphological properties, including color hue and clay content, show positive trends with deposit age in a similar fashion to chronosequences found in other regional physiographic provinces despite differences in climate and parent materials. Maximum color hue increased from 10YR on Qt5 (~4 ka) to 2.5YR on Qt1-3 (~1,470-128 ka) (Table 1; Fig. 6). This trend of progressive reddening has been shown in other regional chronosequence studies (e.g.

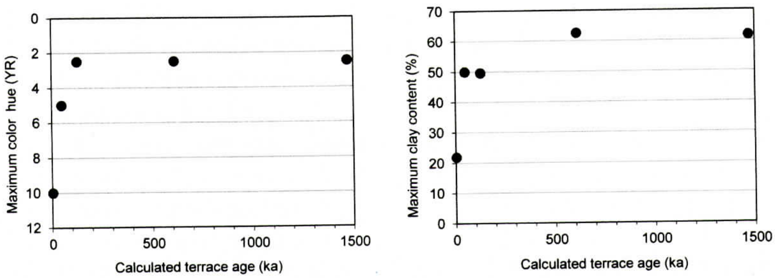

Fig. 6. Chronofunctions of color hue and clay content for representative terrace soils. Plots show maximum values obtained from the B horizon. Estimated ages for terrace units are: 4 ka (Qt5), 50 ka (Qt4), 128 ka (Qt3), 610 ka (Qt2), and 1,470 ka (Qt1).

Foss et al., 1981; Leigh, 1996) and is explained by the progressive accumulation of pedogenic iron oxides in the soil (see below). Color hue was found to plateau at 2.5YR on Qt3 deposits, which are calculated to be ~128 ka in age. Foss et al. (1981) found that hues of 2.5YR typically occurred in colluvial and alluvial Piedmont soils believed to be older than 100,000 years.

In addition to color hue, clay content has typically been found to increase as a function of soil age in a variety of settings throughout the southeastern and eastern United States (e.g. Howard et al., 1993; Leigh, 1996; Engel et al., 1996) regardless of changes in climate and parent material. In our field area, maximum clay content of the B horizon increased from ~25% in Qt5 soils to ~62% in Qt1 soils (Fig. 6). Observed clay contents are similar to those published in other regional chronosequences for soils of similar ages. For example, Engel et al. (1996) reported clay contents of ~53% in soils of Early Pleistocene age (~770-970 ka) from the Piedmont of Pennsylvania, which developed in diamictic alluvium. Maximum measured clay content appears to reach an asymptote at approximately 60% for terrace units Qt2 (~610 ka) and Qt1. This trend in clay content likely represents an internal threshold, such that the high clay content either prevents further illuviation (Howard et al., 1993) or promotes runoff and surface degradation. There is a break in slope, however, in the clay content chronofunction at ~50 ka (Fig. 6) with an unexpectedly higher proportion of clay for the Qt4 deposit (see also Fig. 4). A likely explanation for this high clay content in Qt4 soils relative to older Qt3 (~128 ka) soils is that the clay in Qt4 was derived from inheritance of an older, previously weathered clay-rich soil, presumably eroding off of drainage basin hillslopes.

Dithionate extractable iron (Fe_d) was found to increase progressively with age from 3.63% on Qt5 to 6.37% on Qt1 (Fig. 5). Regional studies have found similar increases in Fe_d with age despite differences in parent material, e.g. soils developed in alluvial and eolian deposits in the Valley and Ridge and Piedmont of Pennsylvania (Engel et al., 1996). The rate of Fe_d formation has been shown to initially increase rapidly but then decline with time due to a progressive reduction in the availability of fresh mineral surfaces to weather (McFadden and Hendricks, 1985; Birkeland, 1999). Our results echo this trend with Fe_d reaching a penultimate level of ~6.3% on Qt2 deposits. A close relationship has been shown to exist between Fe_d and clay content in soils (e.g. McFadden and Hendricks, 1985) because both are weathering products that progressively accumulate in a soil profile through time. Our results support this relationship, showing a strong positive correlation between these variables (R^2 value of 0.958) (Fig. 5).

Changes in iron content related to pedogenesis are commonly expressed through the iron activity ratio (Fe_o/Fe_d) rather than in absolute amounts. This ratio negates the difference in the initial Fe_o content of the parent material and emphasizes the formation of crystalline iron oxides due to weathering processes. Generally, this ratio decreases with time as amorphous iron oxides (Fe_o), which are the initial precipitate, convert to more stable, crystalline oxides (Fe_d) over time (e.g. McFadden and Hendricks, 1985; Birkeland, 1999). This declining trend has been documented in other chronosequence studies under a variety of climates (e.g. McFadden and Hendricks, 1985; Shaw et al., 2003; Eppes et al., 2008). In the Catawba River terrace soils, we observe a decline in Fe_o/Fe_d with deposit age between Qt4 and Qt5 time (~50-4 ka) and between Qt1, Qt2 and Qt3 time (~1,470-128 ka; Fig 5). Maximum Fe_o/Fe_d values, indicating relatively low degrees of iron crystallinity due to weathering processes, were found in Qt3 deposits. Data also indicate that the youngest deposits (Qt4 and Qt5) have the lowest ratios of amorphous to crystalline iron oxides. The observed drop in Fe_o/Fe_d ratios between Qt3 and Qt4 time can be attributed to change in sediment provenance of the Catawba River. It is likely that the low Fe_o/Fe_d ratios, which indicate high proportions crystalline iron oxides relative to amorphous iron oxides, in Qt4 and Qt5 deposits result from the presence of reworked, previously weathered material. As such, the Fe_o/Fe_d ratios in these two terraces are the product of inheritance rather than in situ soil development. It is possible that Qt3 and older soils were eroded in portions of the landscape and that stripped material was deposited during Qt4 time. These data therefore have implications for regional landscape evolution (see below).

In our study, other soil morphological characteristics such as structure, complexity of horizonation, solum thickness and Bt horizon thickness were not found to be useful indicators of relative age as they have been in other studies (e.g. Foss et al., 1981; Markewich and Pavich, 1991; Engel et al., 1996). Soil structure increased in grade from moderate to strong with terrace age (Table 1) however no quantifiable trend was identified. The weak trend in structure is likely due to the high clay content in all terrace soils, which is an important factor in the formation of blocky structure (e.g. Birkeland, 1999). The lack of any trend in horizon complexity is attributed to the relatively rapid formation of Bt horizons in the study area. Clay films are present in all terrace units although they are less prominent in the lowest terrace soils (Qt5). Our data suggests that Bt horizons form in Piedmont soils in as little as 4,000 years. However, this rapid rate of formation may be a function of the clay contributions from previously weathered, reworked material that we discuss above. Most soil pits could not be dug deep enough to expose unweathered parent material (C horizon) and therefore solum and Bt horizon thickness could not be accurately determined.

Landscape Evolution

The apparent increase in soil development around Qt4 time reflected in the chronofunctions of both clay content and Fe_o/Fe_d ratios could conceivably result from an increase in weathering rates due to wetter or hotter climatic conditions. There is no paleoclimatic data, however, which indicates that overall time period was particularly warmer or wetter than any other warm-wet period in the past. Instead, we conclude that sediment deposited at that time was largely derived from erosion of previously weathered materials in the Catawba River basin (Figs. 5 & 6). We suggest that between Qt3 & Qt4 time (128-50 ka), the primary sediment source for the Catawba River switched from relatively unweathered bedrock, likely derived from incision into channel bottoms, to relatively well developed soils stripped from hillslopes and/or eroded by lateral migration of the river channel into older terraces in valley bottoms. Such a switch represents a major change in the overall landscape evolution of the Catawba basin at that time. Studies have shown that the character of alluvial deposits reflects the erosional history of the source area as well as the dynamics of the river transporting sediment (e.g. Schumm, 1981). The lack of coarse quartzite gravels in Qt4 deposits suggests that the Catawba River also experienced a decrease in stream power during this time period, which resulted in the crossing of a threshold, such that the river could no longer transport coarse cobble gravel clasts (e.g. Bull, 1979; Schumm, 1979). This overall decrease in competency was likely ongoing from Qt3 time when the percentage of coarse gravels significantly decreased from previous terrace deposition episodes. Furthermore, it is possible that finer sediments, which previously would have been transported downstream to the coastal plain, began to be deposited at higher reaches in the Piedmont as discharges decreased.

The implication from these data is that the observed change from a cobble gravel regime to a sand regime and the change in sediment source between 128-50 ka was driven by a significant forcing event such as climate change or base level change. It is unlikely that Piedmont terraces were formed by eustatic changes in base level, however, since the upstream range of Quaternary eustatic influences is thought to be limited and only in the Coastal Plain (e.g. Leigh and Feeney, 1995). Lack of absolute dating of our studied terraces as well as of good paleoclimate data for this region of the Southeast preclude drawing strong conclusions regarding climate forcing, however, some general connections can be made.

Climatic fluctuations often alter the relationship between sediment supply and discharge in alluvial systems through changes in precipitation, vegetation cover and runoff patterns (e.g. Bull, 1991). Leigh (2008) summarizes the findings of limited studies that document the existence of riverine dunes and braid deposits between 70-30 ka in southeastern Coastal Plain rivers, whose basins extend into the Piedmont. These types of deposits are consistent with the high sediment supply that we infer for the Catawba River during the middle of this time interval. The period around 50 ka sits within the MIS 4 cold period, and it has been suggested that much of this period in the Southeast was characterized by cool climatic conditions (e.g. Leigh, 2008). Cold climatic regimes are typically thought to increase sediment supply by increasing physical weathering processes and removing vegetation cover from hillslopes, which promotes the mass movement of sediment to the valley floor. Eaton et al. (2003) present a model of landscape evolution for the central Blue Ridge which indicates enhanced debris flow activity and debris fan progradation during colder Late Pleistocene climates. It is therefore probable that Qt4 alluvium was deposited around 50 ka due to increases in sediment supply, delivered from basin hillslopes, and decreased discharge resulting from cold climates. Calculated ages for all other terrace units, however, correlate with warm, interglacial time periods. For example, the age of the Qt3 unit (~128 ka) corresponds with the peak interglacial high stand during MIS 5e. A possible reconciliation of the observed terrace formation during these different climatic regimes is that the Qt4 terrace is a fill terrace, whereas older terraces are strath terraces. If correct, the Qt5 unit may be a fill-cut terrace formed in the Qt4 alluvium. Unfortunately, the lack of outcrops in the study area precludes drawing firm conclusions regarding the nature of terraces.

CONCLUSIONS

Soils in the Piedmont appear to vary predictably over time in terms of the development of certain soil properties. In particular, color hue, pedogenic iron (Fe_d) and clay content appear to be the most useful indicators of relative soil development for these Piedmont soils. Results, highlighting the development of these properties over time, are analogous to other studies (e.g. Engel et al., 1996; Leigh, 1996; Shaw et al., 2003) outside of the Piedmont and developed in other parent materials implying a regional consistency as a function of age. These soil characteristics progressively increase with age up to approximately 128,000 years after which the rate of development plateaus indicating the attainment of a developmental threshold. Howard et al. (1993) found that after an early, rapid phase of soil formation, soils in the fall zone of Virginia had attained a more or less steady state by about 100,000 years. Our results imply that steady state conditions in Piedmont soils occur around the same time or perhaps slightly later. This pattern of development indicates that while these soil properties show positive trends with increasing age they are less useful for correlating and establishing relative ages of older soils (i.e. older than 128,000 years) as their development is approaching or has attained a form of equilibrium. The trend in clay content specifically, represents a threshold where the high clay content of the soil prevents further illuviation as found in other studies (e.g. Howard et al., 1993). Fe_o/Fe_d results indicate a break in soil development between Qt3 and Qt4 time (~128-50 ka), which is attributed to the erosion of relatively well developed soils from local hillslopes and/or valley bottoms. Evidence derived from soil development, fluvial landforms and sedimentological changes allow us to make tentative assertions concerning the geomorphic history of the Catawba River. This history can be summarized as one of overall incision, coupled with a lowering of peak discharges over time, punctuated by periods of aggradation that may be driven by increases in sediment supply during cold climatic conditions, at least in the latter history of the river.

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A NEW SPECIES OF *PARADIABOLOCRINUS* FROM THE UPPER ORDOVICIAN OF CENTRAL KENTUCKY, USA

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ABSTRACT

A new species of camerate crinoid, *Paradiabolocrinus teres*, is described from the Upper Ordovician (Soudleyan-Marshbrookian), Curdsville member of the Lexington Limestone (Central Kentucky, USA). This new crinoid lacks the prominent ornamentation that defines other species within the genus. This species yields new information regarding the morphology of the genus preserving the first intact crown and proximal stem. In addition, apparent ontogenetic patterns observed within *P. teres* strength the position of *P. stellatus* within this genus.

INTRODUCTION

The Ordovician radiation is one of the pivotal events in the history of life in that it displayed a drastic increase in diversity of the phyla originating during the Cambrian explosion and also represented a substantial increase in ecological complexity (Webby et al. 2004; Bambach et al. 2007). Echinoderms and crinoids, in particular, are an important component of Paleozoic marine ecosystems and played a major role in the Ordovician radiation (Sprinkle and Guensburg 2004).

Crinoid diversity was low during the beginning of the Ordovician, nearly tripled during the Soudleyan, plateaued until Silurian fluctuations, caused by the Ordovician mass extinction (Peters and Ausich 2008). The Sandbian (Soudleyan/Marshbrookian) interval is particularly important because of its position immediately following the diversification that can potentially yield information regarding the ecological and evolutionary consequences of a large increase in diversity (both regionally and locally). Another metric for understanding macroevolution is disparity, which measures not the changes in the number of species (diversity), but how different those species are from one another (Runnegar 1987). Crinoid disparity has been extensively studied (Foote 1994, 1999) and the most recent work (Deline and Ausich 2011) shows a high initial disparity before the Ordovician radiation, a plateau during the Late Ordovician, and a rise during the Early Silurian recovery. The early Late Ordovician is particularly important because it is typified by a growing separation in morphology between the subgroups of crinoids while those groups simultaneously contracted to a more uniform shape, which caused a slight drop in overall crinoid disparity (Deline and Ausich 2011).

In order to understand the evolutionary and ecological ramifications of the Ordovician radiation, we need a clear understanding and description of the fauna during this critical interval. Gaining a better understanding of the constituency of the community will also allow a better interpretation of the ecological pressures that may have influenced adaptation on the local scale.

LOCATION AND GEOLOGIC SETTING

The new specimens are from the Lexington Limestone of Central Kentucky along a broad road cut on Kentucky Route 34 east of the bridge crossing the Kentucky River, near Dansville, Garrard County, Kentucky, USA (Fig. 1). The Late Ordovician Lexington Limestone is a heterogeneous unit of bioclastic carbonates bounded below by the lithographic Tyrone

Figure 1. Location of the exposure of the Curdsville member of the Lexington Limestone near Dansville, Garrard County, Kentucky.

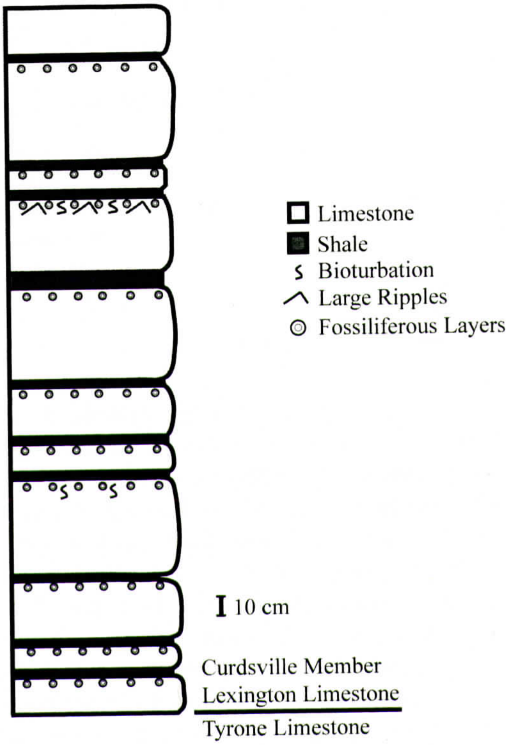

Figure 2. Stratigraphic column of the exposure of the Curdsville member, Lexington Limestone at the Kentucky 34 road cut. Intact echinoderms are preserved at multiple levels on the top of the limestone underlying thin shale units. The specimens of *Paradiabolocrinus teres* were found at different horizons within the member.

Limestone and above by the shale dominated Clays Ferry Formation (Cressman 1973). The lowermost unit of the Lexington Limestone, the Curdsville Member, has a diverse and well-preserved fauna that is similar to the Hull Limestone of Ontario (Springer 1911). The Curdsville Member is poorly exposed at a limited number of outcrops and the nature of the exposure prevents the recovery of large numbers of specimens, limiting the study of this important fauna. The Curdsville Member is composed of horizontally bedded, massive, and highly fossiliferous packstones with a diverse assemblage of sponges, brachiopods, bryozoans, and trilobites. In addition, there is a rich echinoderm assemblage including crinoids (Springer 1911; Parsley 1981), edrioasteroids (Bell 1979; Sumrall and Deline 2009), paracrinoids (Parsley 1981; Sumrall and Deline 2009), stylophorans (Parsley 1981), and cyclocystoids (Parsley 1981).

The limestone bedding surface is uneven and extensively burrowed. The presence of direct attachment to the substrate by edrioasteroids and crinoids holdfasts indicates the development of firm- to hardgrounds. Large ripples are present on the bedding plane, which indicates high-energy deposition. In between the large-scale ripples are muddy shale lenses that were deposited in the topographic lows that commonly preserved intact echinoderm remains (Cressman 1973). This pattern of thin shale layers preserving intact echinoderms is repeated throughout the section with the bulk of the unit composed of massive limestones that contain taxonomically uninformative disarticulated and highly abraded fossil hash (Fig. 2).

Based on examinations of sequence stratigraphy, biostratigraphy (conodonts and graptolites), and dating k-bentonites (Brett et al. 2004), the Curdsville Member of the Lexington Limestone has been placed within Soudleyan to Marshbrookian stages of the Caradoc Epoch of the Late Ordovician, which corresponds to the Katian Stage of the Upper Ordovician of Bergström et al. (2006).

PREVIOUS INVESTIGATIONS

Paradiabolocrinus Brower and Veinus was first described in 1974 based on two specimens from either the Benbolt or Wardell Formations of Tennessee and Virginia and a redescription of a single specimen originally described as *Diabolocrinus asperatus?* from the Benbolt or Dryden formation also of Tennessee and Virginia. This genus was described as being similar to *Diabolocrinus* but differing by having smaller and less protuberant arm bases, numerous (17-36) and irregular interarea plates, and interradidials positioned as distally as fixed secundibrachials. In 1982, Kolata tentatively added a third species to this genus from the Upper Echinoderm Zone of the Mountain Lake Member, of the Bromide Formation of Oklahoma. This species, *Paradiabolocrinus stellatus*, possesses abundant and irregular interradials, but the interradials at the level of secundibrachials are either very small or absent. All three of these species have abundant ornamentation on their calyx plates in the form of protruding nodes, sinuous ridges, or large protruding ray ridges. The new species is younger stratigraphically and lacks this defined ornamentation. It is also better preserved yielding insights into the morphology of the stem and crown. Both specimens of this new species have been reposited in the collections of the Cincinnati Museum Center, Ohio.

SYSTEMATIC PALEONTOLOGY

Subclass CAMERATA Wachsmuth and Springer, 1885

Order DIPLOBATHRA Moore and Laudon, 1943

Family RHODOCRINITADAE Bassler, 1938

Genus PARADIABOLOCRINUS Brower and Veinus, 1974

Type Species— *Paradiabolocrinus irregularis* Brower and Veinus, 1974

Diagnosis— A rhodocrinitid crinoid with a low to medium globose to bowl shaped cup; median ray ridges; stellate ridges on the basal and radial plates; tegmen with lobate ambulacral areas and smooth surface; two arms per ray; small, numerous, and irregular interaradials including a small number at the level of fixed secundibrachials.

Discussion— Based on the phylogenetic work of Ausich (1998), *Paradiabolocrinus* is most closely related to *Bromidocrinus* and *Diabolocrinus* based on similar ray structures and extensive interareas. *Paradiabolocrinus* differs from *Diabolocrinus* in that *Paradiabolocrinus* has interradial plating at the level of secundabrachials and small, numerous, and irregular, interradial plates. Contrary to the discussions of Brower and Veinus (1974) and Kolata (1982), Ausich's (1998) analysis linked *Paradiabolocrinus* more closely to *Bromidocrinus* based on shared ray structures and small, irregular interarea plates. These two genera differ, however, in that *Bromidocrinus* has an elongate and larger calyx with prominent grooves at the base of the cup, while lacking interradial plates between fixed secundibrachials.

Occurrence— Late Ordovician (Caradoc; Harnagian –Marshbrookian); United States (Kentucky, Oklahoma, Tennessee, and Virginia).

Paradiabolocrinus teres Hearn and Deline, n. sp.

Figures 3 and 4

Diagnosis— *Paradiabolocrinus* with minor stellate ridges on its relatively smooth calyx plates (lacking nodes or sinuous ridges); minor ray ridges leading to non-protruding arm facets; broad ray branches with prominent interradials fixed to the level of secundibrachials; large interareas with small irregularly shaped interradials with a medium to large central plate in the interradials.

Description— Species represented by two specimens with a complete calyx and crown. Aboral cup low, globose shape, with a flat base. The holotype is 7.2 mm in height and 13.2mm wide; arm bases lobate and minorly protuberant. Cup plates slightly convex, ornamented with stellate ridges; minor ray ridges that con-

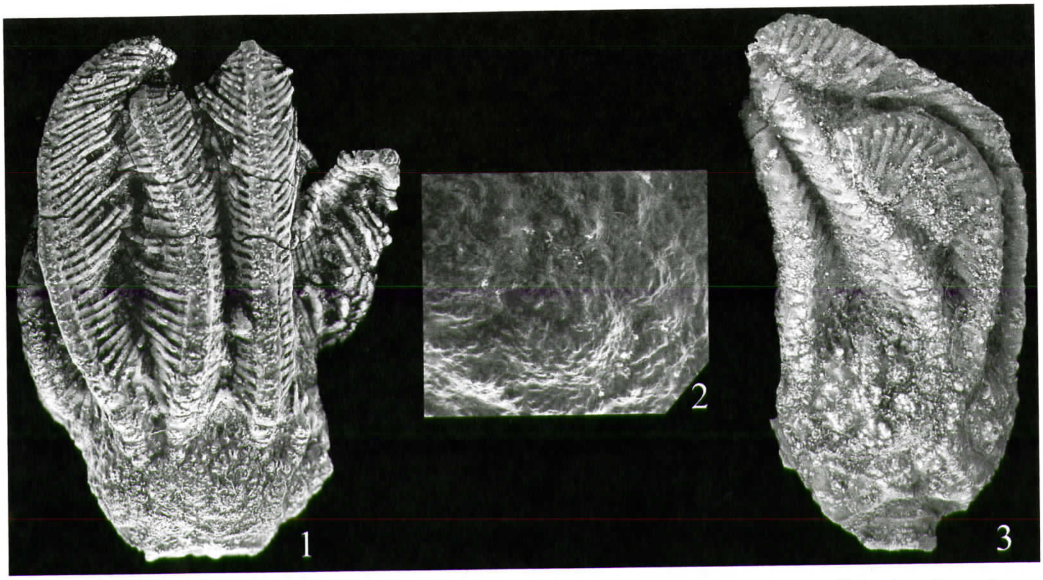

Figure 3. Photographs of holotype IP63954 and paratype IP63955 of *Paradiabolocrinus teres* n. sp. *1,* AB interray of the holotype showing the numerous interray plates and the interradials at the position of fixed secundibrachials, though the distinctness of the plates has been reduced through preparation. The arms which are very similar to *Diabolocrinus* are also shown, whitened, X4.5; *2,* Scanning electron microscope image of the interradial of the holotype showing the numerous interray plates, X7; *3,* CD interay of the paratype showing the medial anal series, whitened, X4.1.

sist of the convergence of stellate ridges on the basals that lead to the radials. Stellate ridges terminate on the first primibrachial; median ray ridges form a prominent stellate pattern in basal view.

Infrabasals 5, confined to the basal cavity. Basals 5, 2.1 mm high and 3.4 mm wide, hexagonal to heptagonal, in contact with 2 infrabasals, 2 basals, 2 radials, and 2 to 3 interradials. Radials 5, 2.7 mm high and 3.4 mm wide. Primibrachial 1 height and width approximately equal. Primibrachial 2 wider than high, axillary. The shape of the radials and primibrachials vary because of irregular plating within the interarea. A single interradial is present between primibrachials 1 and 2; Secundibrachial 3 bears fixed pinnule on interray side.

Interrays relatively wide; 30-40 plates below level of secundibrachial 3, with 2 plates at the base of the interray. Interradial area consisting of 1 large plate surrounded by small supplementary plates. Interbrachials small, numerous, and irregular. CD interray (obscured in the holotype, but is preserved in the paratype) widest area containing the medial anal series, which consist of 5 relatively large plates. Primanal is not distinct; tegmen unknown.

Arms 10, free after secundibrachial 3, uniserial and cunneate proximally grading rapidly into biserial brachials (1/10 arm length). The pinnules are broad and composed of approximately 10 pinnulars. Arms 30.5 mm long on holotype, crown is approximately 4.2 times the cup height.

Stem known only from proximal section. Heteromorphic, round columnals, nodal broader with two lateral extensions. Columnals thin; lumen small and pentagonal; symplectic articulation.

Discussion—This species is based on two specimens that have well preserved crowns. Their calyces has been somewhat abraded although not uniformly which allows a description of the fine ornamentation on the specimens. This species differs significantly from *Paradiabolocrinus stellatus* and *P. sinuorugusus* but closely resembles *P. irregularis*. The new species differs from *P. stellatus* in having muted ray ridg-

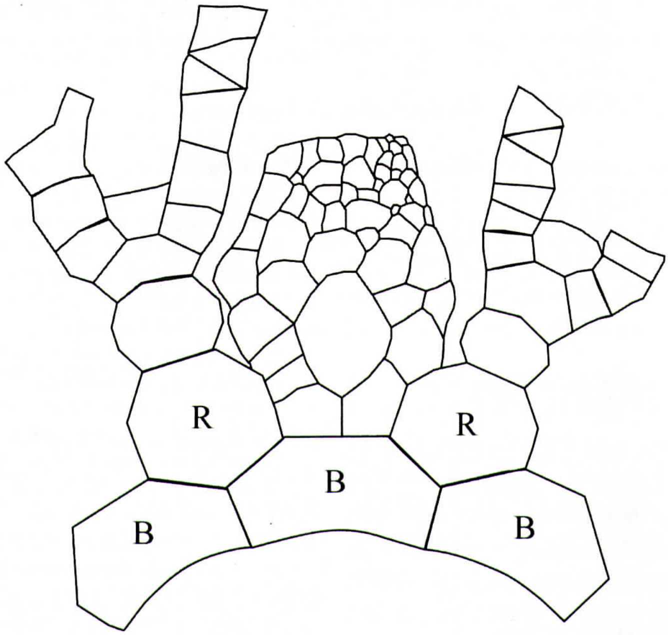

Figure 4- Camera lucida drawing of the B interray of holotype IP63954 of *Paradiabolocrinus teres* n. sp. Note the presence of numberous interray plates and a single interradial plate at the position of secundibrachials. This plate is missing in the paratype IP63955, though it still contains numerous interray plates. X7.6.

es, which are barely raised above the interarea plates leading toward less protrusive arm facets. *Paradiabolocrinus stellatus* also has a narrow ray branch, which causes the most distal interradials to be minuscule or completely absent, which sets this crinoids apart from all of the other species within the genus. *Paradiabolocrinus teres* differs from *P. sinuorugosus* in that it lacks the prominent sinuous ridges that cover the cup plates and the two crinoids have different cup shapes in that the former is globose and the latter is more linear forming a conical cup. Finally, the position of the arm facets varies in *P. sinuorugosus* between the third and fifth secundibrachial causing an offset in the free arms while the arms become free uniformly in *P. teres* at the fourth secundibrachial. The new species differs from *P. irregularis* in that it lacks large nodes on its calyx plates and has a taller globose cup shape. *Paradiabolocrinus teres* is the only species within the genus to have a well-preserved crown, which is very similar to that of *Diabolocrinus* in that they have cuneate proximal brachials leading to massive biserial arms that bear long pinnules. The similarity of the crown morphology to a closely related genus indicates that this morphology is likely shared by all of the members of *Paradiabolocrinus*.

The smaller second specimen of *Paradiabolocrinus teres* lacks clear interradial plating between adjacent secundibrachials, such that it may be missing or miniscule as is the case in *P. stellatus*. This second specimen still has the large number of interadial plates, which places it within *Paradiabolocrinus*. It is possible that the addition of plates between secundibrachials occurs later in ontogeny of the species and, thus, is lacking in younger individuals. However, a larger sample is required to test this growth pattern. If this is the case, these plates might easily be lost with small shifts in development. Nevertheless, the presence of interradials at the level of secundibrachials is likely a poor diagnostic character for this genus and an increase in the number of interradial plates compared with *Diabolocrinus* should be used to distinguish these two genera. This also strengthens the placement of *P. stellatus* within this genus.

Type— The holotype is IP63954 and the paratype is IP63955 at the Cincinnati Museum Center.

Occurrence— The holotype and paratype were found in the Curdsville Member, Lexington Limestone at the outcrop along Kentucky Route 34, near Danville, Garrard County, Kentucky.

Name— The specific name refers the smooth, unornamented texture on the cup plates.

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AN *APHELASPIS* ZONE (UPPER CAMBRIAN, PAIBIAN) TRILOBITE FAUNULE IN THE CENTRAL CONASAUGA RIVER VALLEY, NORTH GEORGIA, USA

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ABSTRACT

Middle and Upper Cambrian strata (Cambrian Series 3 and Furongian) in the southernmost Appalachians (Tennessee to Alabama) comprise the Conasauga Formation or Group. Heretofore, the youngest reported Conasauga beds in the Valley and Ridge Province of Georgia were of the late Middle Cambrian (Series 3: Drumian) *Bolaspidella* Zone, located on the western state boundary in the valley of the Coosa River. Two new localities sited eastward in the Conasauga River Valley, yield a diagnostic suite of trilobites from the Upper Cambrian *Aphelaspis* Zone. Very abundant, polymeroid trilobites at the primary locality are referable to *Aphelaspis brachyphasis,* which is a species known previously in western North America. A second locality has produced a few identifiable specimens of the aphelaspine *Eugonocare* (*Olenaspella*) *separatum*. Specimens at these two localities are generally complete individuals compressed in tan mudstones. The primary locality features abundant body cluster accumulations, implying mass mortality by bioimmuration. The trilobite assemblage also includes the agnostoids *Glyptagnostus reticulatus*, *Agnostus inexpectans*, and *Aspidagnostus rugosus*, all correlated to the global Paibian agnostoid *Glyptagnostus reticulatus* Zone. These localities contain the southeastern-most Late Cambrian faunule in the Appalachians. The trilobite species and carbonate-free, mudstone lithology, lacking evidence of infaunal bioturbation and burrowing, suggest accumulation eastward of a paleotopographic shelf-to-basin break, which is interpreted to be east of the Alabama Promontory and in the Tennessee Embayment. The preservation of abundant aphelaspine specimens by bioimmuration events may have been the result of mudflows down the shelf-to-basin slope.

INTRODUCTION

Trilobites and associated biota from Middle Cambrian beds of the Conasauga Formation in northwestern Georgia have been described by Walcott, 1916a, 1916b; Butts, 1926; Resser, 1938; Palmer, 1962; Schwimmer, 1989; Schwimmer and Montante, 2007. These fossils and deposits come from exposures within the valley of the Coosa River, in Floyd County, Georgia, and adjoining Cherokee County, Alabama. Trilobite biozone associations of these Middle Cambrian biotas are of the *Glyphaspis* to *Crepicephalus* Zones of the traditional Laurentian Middle Cambrian Series.

Cambrian trilobites have not been described farther east- or southward from the above in the southern Appalachian outcrop, although the Conasauga Formation is exposed in a separate fault-bounded slice in the Conasauga River Valley (Figure 1). We report here new Upper Cambrian localities in this outcrop, containing the southeastern-most Cambrian trilobites in North America. The new trilobite assemblages include polymeroids of the Laurentian Upper Cambrian *Aphelaspis* Zone, including *Aphelaspis brachyphasis* and *Eugonocare (Olenaspella) separatum*; and coeval agnostoids of the global *Glyptagnostus reticulatus* Zone, including *Glyptagnostus reticulatus*, *Agnostus in-*

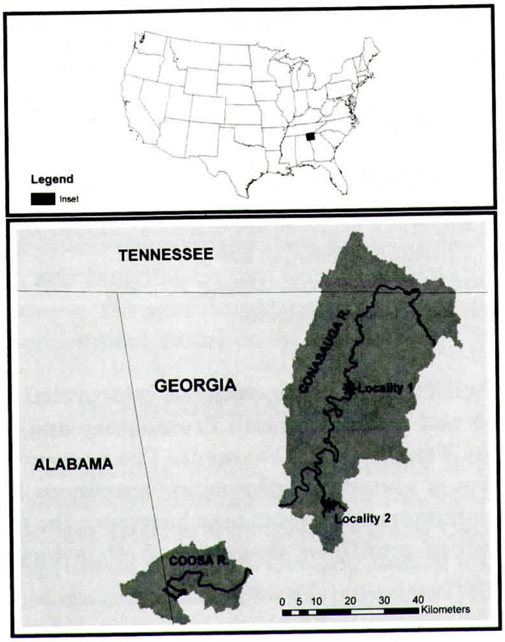

Figure 1a— Map of Conasauga Formation outcrops in Georgia with *Aphelaspis* Zone localities in the Conasauga River Valley indicated, also showing the general geographic position of the trilobite beds (discussed in text) in the proximal Coosa River Valley.

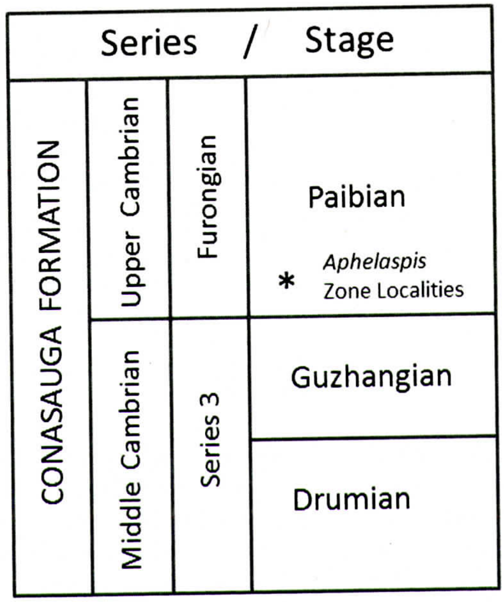

Figure 1b—correlation chart showing the stratigraphic position of the *Aphelaspis* faunule. (Correlation chart based on Babcock and Peng, 2007, and Ogg, 2009).

expectans, and *Aspidagnostus rugosus*.

In contrast with most prior reports of Upper Cambrian trilobites from the Southern Appalachians (e.g. Butts, 1926; Resser, 1938; Palmer, 1962; Rasetti, 1965), specimens collected in the new localities are preserved in mudstones as compressed, typically complete individuals, with intact librigenae. At Locality 1 (Figure 1a), *Aphelaspis* specimens are very abundant, with intact librigenae, associated in "body clusters" (*sensu* Whittington, 1997b), and commonly surrounded by decay-gas induced iron oxide halos (Schwimmer and Montante, 2007). These new trilobite localities contain relatively few agnostoids, but enough species are present (as indicated above) to be clearly referable within the global Cambrian agnostoid-based stratotype system (Peng and Robison, 2000; Babcock and others, 2007; and see discussion in "Biostratigraphy"). In addition to extending the southeastern geographic range of Upper Cambrian strata in the southern Appalachians, the occurrence of a well-demarcated *Aphelaspis* assemblage with the globally-correlative agnostoid *Glyptagnostus reticulatus* Zone provides well-dated Upper Cambrian sites in the south-easternmost Appalachians.

GEOLOGIC SETTING

The localities here are in the Conasauga Formation in Murray and Gordon Counties, northwestern Georgia. This study area (Figure 1a) is in the Appalachian Valley and Ridge Province, characterized by series of northeast-trending, ridge-forming Paleozoic thrust faults and transforms, with relatively low valleys floored with less-resistant strata sandwiched between fault boundaries. The mudstones of the Conasauga Formation form two such valleys (Figure 1a), and the two localities discussed here lie in the broad valley of the Conasauga River, situated between the East Coosa and Cartersville Faults (Thomas and others, 2000; Thomas and Bayona, 2005). Locality 1 is a riverside outcrop on the Conasauga River in Murray County, in the vicinity of Chatsworth, Georgia, on the eastern side of the Conasauga River Valley. This locality has an approximately 4.0 meter-thick exposure of abundantly fossiliferous, tan-to-olive, flaggy-bedded mudstones exposed on the banks of the river and in ancillary drainages. Polymeroid trilobites are very abundant at this site, and include numerous individuals with attached librigenae. Locality 2, which is now covered, was a commercial borrow-pit excavation in the vicinity of Calhoun, Georgia, in southernmost Gordon County, exposing approximately 6.0 m of olive-green mudstones with a relatively sparse trilobite fauna. This locality is in the southwestern-most edge of the Conasauga River Valley.

The Conasauga Formation in northwestern Georgia spans much of the Middle Cambrian (Schwimmer, 1989, Schwimmer and Montante, 2007) through the lowermost Upper Cambrian (Figure 1b). Collections for this report are from exposures in the upper portion of the Conasauga Formation in Georgia. The Conasauga in its entire geographic range, extends down to the base of the Middle Cambrian, up through most of the Upper Cambrian, and is mapped from central Alabama, across northwestern Georgia, to eastern Tennessee and southwestern Virginia (Palmer, 1971; Hasson and Hasse, 1988; Osborne and others, 2000), reaching local thicknesses exceeding 1000 m. Across the entire exposure, the Conasauga represents multiple depositional environments forming on the marine shelf and in shelf-edge basins along the salients and recesses of the Laurentian margin of the Cambrian Iapetus Ocean. These paleoenvironments include shallow-water peritidal clastic wedges, admixed outer shelf carbonates and shales, and algal carbonate shoals on the shelf-to-basin boundaries (Hasson and Haase, 1988).

BIOSTRATIGRAPHY

Trilobites from both new localities are assigned to the *Aphelaspis* Zone (Figure 1b), which is coeval with the lowermost biozone of the global of the Furongian Series (= Upper Cambrian in traditional Laurentian nomenclature: Ludvigsen and Westrop, 1985). The Conasauga sites in consideration are assigned to the *Aphelaspis* Zone based on the co-occurrence of *Aphelaspis brachyphasis*, and *Eugonocare (Olenaspella) separatum* (Palmer, 1962, 1965; Pratt, 1992).

The base of the *Aphelaspis* Biozone is biostratigraphically equivalent to the first appearance of the agnostoid *Glyptagnostus reticulatus* (Babcock and others, 2005). This species is the eponym of the biozone that comprises the lowest unit of the global Paibian Stage (Gradstein and others, 2005; Babcock and Peng, 2007), which is penecontemporaneous with the Laurentian Steptoean Stage (Ludvigsen and Westrop, 1985; Peng and others, 2004). The new Conasauga sites include three agnostoid species common to the *Glyptagnostus reticulatus* Zone (Peng and Robison, 2000), including *G. reticulatus* itself. Therefore, these Conasauga sites include age-specific genera and species incorporated in both Laurentian polymeroid- and global agnostoid trilobite chronostratigraphic zone concepts.

SYSTEMATIC PALEONTOLOGY

Repository and Terminology

Specimens described and figured are curated and housed in the Cambrian Research collections (CSUЄ) of Columbus State University, Columbus, Georgia. Descriptions of polymeroid trilobites follow Whittington (1997a); agnostoid morphology also incorporates basic terminology from Öpik, 1967, as modified by Whittington and Kelly, 1997, and Peng and Robison, 2000. To protect fragile fossil sites, only general localities are given here and in Figure 1a: precise locality coordinates are available for qualified research by contact with the first author.

Order Agnostida Salter, 1864
Subfamily Agnostinae M'Coy, 1849
Agnostus Brongniart, 1822
Agnostus inexpectans Kobayashi, 1938
Figure 2.1

Referred Material— CSUЄ-07-4-1, a complete exoskeleton, part and counterpart; CSUЄ-07-4-2, an incomplete cephalon.
Occurrence— Locality 1, Murray County, Georgia (see Figure 1a).
Diagnosis—Cephala with moderate to deep median preglabellar furrow, transglabellar furrow relatively shallow, glabellar furrows F1 and F2 well-incised, subtending distinct M2 and M3. Pygidium slightly expanded posteriorly, posteroaxis not touching border furrow, F1 continuous across pygidial axis, F2 weakly demarcated around axial node.
Discussion—Peng and Robison (2000) provded a complete review of this genus and species, including its various reassignments between *Innitagnostus* and *Agnostus*. The agnostoids in the sites to be discussed here tend to be poorly preserved at the microscopic level, and also tend to split from the enclosing matrix with the exoskeleton adhering to one part of the sediment, and the internal cast on the counterpart. The complete individual of *Agnostus inexpectans* figured here (Figure 2.1) has the better preservation on the internal cast.

The specimen figured here, although poorly preserved, shows the characteristic cephalic and pygidial furrows and lobation. Palmer (1962) reported specimens of *A. inexpectans* from the Conasauga Formation in Cedar Bluff, Alabama, located approximately 80 km west of the locality discussed here. *Agnostus inexpectans* is among the most cosmopolitan of Asian, Australian and Laurentian Upper Cambrian agnostoids.

Family Clavagnostidae Howell, 1937
Genus *Aspidagnostus* Whitehouse. 1936
Aspidagnostus rugosus Palmer, 1962
Figures 2.2-2.4

Referred Material— CSUЄ-07-4-8, complete individual; CSUЄ-07-4-9, CSUЄ-07-4-11, cephala; and CSUЄ-07-4-10, CSUЄ-07-4-12, pygidia.
Occurrence—Locality 1, Murray County, Georgia.
Diagnosis—Cephala with sagittally short glabella, edges slightly swollen at M3, genae with irregular, radial scrobiculae with moderately deep furrows, preglabellar medial furrow may be poorly distinct because of cross furrows. Pygidium with elevated, spinose axial nodes, slightly to moderately scrobiculate pleurae, F1 slightly constricted at lateral edges but not subtending distinct M1.
Discussion—*Aspidagnostus* is an easily recognizable, biostratigraphically-useful genus because of the unique pygidial medial spine. The specimens here are very small and poorly preserved, but nevertheless readily identifiable to genus and species.

This species was first identified by Palmer, 1962, in the Conasauga Formation at Cedar Bluff Alabama, in addition to localities in the Great Basin. Subsequently it is has been recognized nearly globally, co-occurring with other agnostoids of the *Glyptagnostus reticulatus* Zone. Pratt (1992) noted that *Aspidagnostus rugosus* occurs in the lowest Steptoean to latest Marjuman strata. Therefore, we assume that the assemblage in study may be likewise constrained to the very oldest portion of the *G. reticulatus* biozone.

Family Indeterminate
Subfamily Glyptagnostinae Whitehouse, 1936
Genus *Glyptagnostus* Whitehouse, 1936
Glyptagnostus reticulatus (Angelin, 1851)
Figures 2.5-2.8

Referred Material—CSUЄ-07-4-3, CSUЄ-07-4-5, CSUЄ-07-4-7 pygidia; CSUЄ-07-4-4, CSUЄ-07-4-6, cephala; plus numerous additional specimens.
Occurrence—Locality 1, Murray County, Georgia
Diagnosis—Complexly scrobiculate agnostoids with narrow border furrows, cephalon

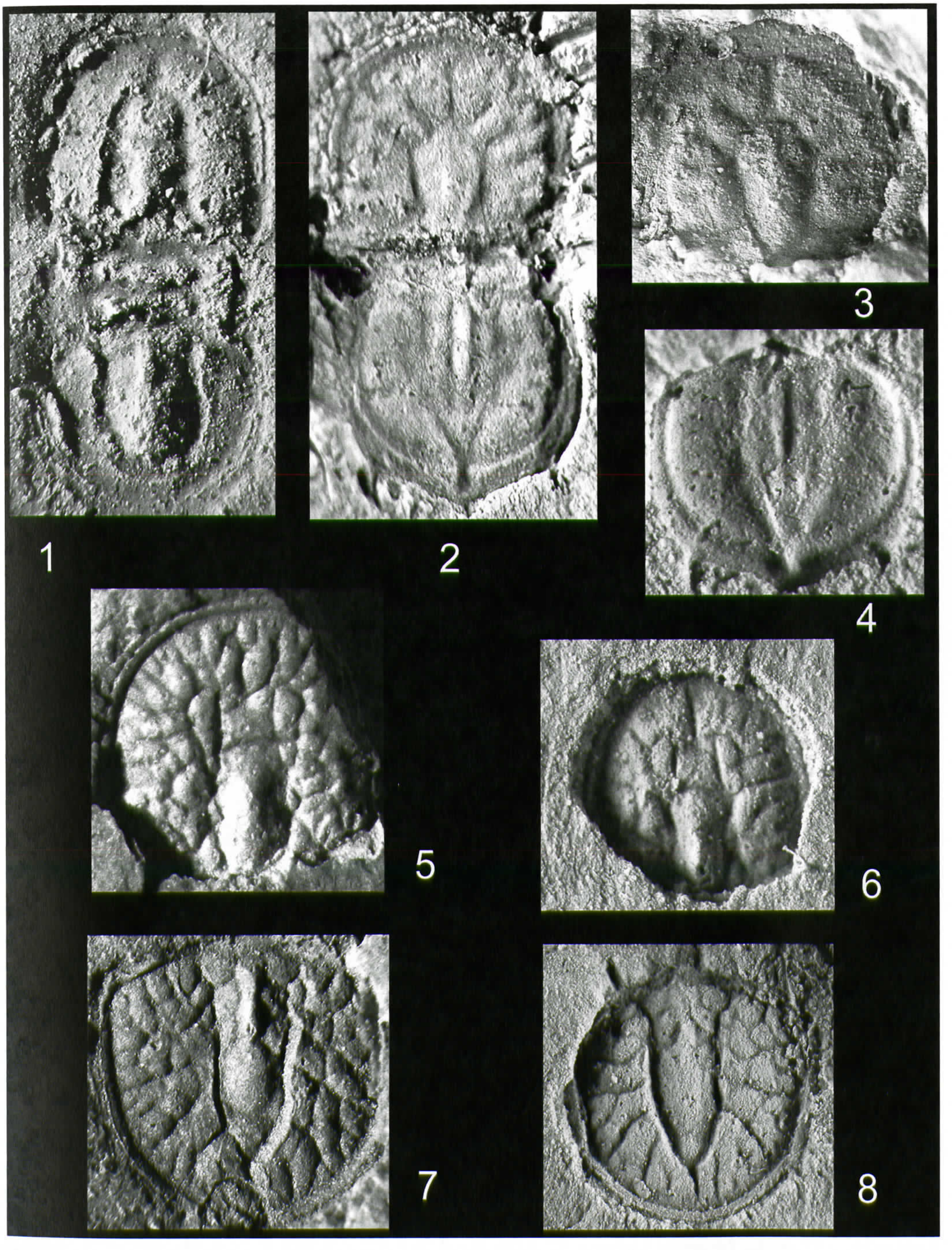

Figure 2—Agnostoid trilobites from Locality 1. *1, Agnostus inexpectans* Kobayashi, internal cast of complete individual, CSU€-07-4-1, x18. *2-4, Aspidagnostus rugosus* Palmer. *2*, complete individual, CSU€-07-4-8, x16; *3*, cephalon, CSU€-07-4-9, *4*, external mold of pygidium, CSU€-07-4-10, both x20. *5-8, Glyptagnostus reticulatus* (Angelin). *5-6* cephala, CSU€-07-4-4, x17, CSU€07-4-6, x15; *7-8*, pygidia CSU€-07-4-3, CSU€-07-4-5, both x15.

with subquadrate anteroglabella, median preglabellar furrow present, basal lobes elongate. Pygidium with tapering axis constricted at M2, not touching border furrow, posterior median furrow present. In some specimens the pattern of rugae is multi-order, forming a nodulose pattern.

Discussion—This is arguably the most distinctive and recognizable agnostoid genus known because of the elaborate and specifically variable scrobiculation on cephala and pygidia. The genus has been discussed exhaustively through one and one-half centuries of literature, and often split into multiple species and subspecies based on the variable patterns of furrows (Shergold, 1982; Pratt, 1992; Peng and Robison, 2000). Species of *Glyptagnostus* are particularly useful, globally distributed guide fossils, and comprise two biozones in the Late-Middle to early-late Cambrian, of which the specimens here denote the younger biozone. It is significant to biogeographic implications of the Conasauga fauna in study (in discussion to follow) that Pratt (1992) noted (p. 87): "…species of *Glyptagnostus* are distributed in slope and deeper shelf lithofacies…."

Resser (1938) and Palmer (1962) described specimens of *Glyptagnostus* from the Conasauga Formation at Cedar Bluff, Alabama, located approximately 100 km southwest of the site of specimens here. Because these had relatively less intensely scrobiculate pygidia, Resser referred the Conasauga Formation specimens to a new species, *G. angelini*, which Palmer (1962) revised as a subspecies, *G. reticulatus angelini*.

Subsequent authors (Pratt, 1992; Peng and Robison, 2000) have observed that the intensity of scrobiculation varies both ontogenetically and temporally in the *Glyptagnostus reticulatus* clade, with geologically older and more juvenile individuals less ornamented. Therefore, it is currently accepted that *G. reticulatus* comprises a single variable species with an apparent cline in complexity of ornamentation that may be useful to delimit the stratigraphic age of specimens. The specimens illustrated here (Figures 2.5-2.8) are mature individuals that show the average intensity of furrows for the stratigraphically older representatives of the species.

Order Ptychopariida Swinnerton, 1915
Suborder Ptychopariina Richter, 1933
Family Pterocephaliidae Kobayashi, 1935
Subfamily Aphelaspinae Palmer, 1960
Genus *Aphelaspis* Resser, 1935
***Aphelaspis brachyphasis* Palmer, 1962**
Figures 3.1-3.7

Referred Material— CSUЄ-07-2-1, CSUЄ-07-5-5, complete holaspides with intact librigenae; CSUЄ-07-5-6, larger holaspis with intact librigenae, missing posterior segments and pygidium; CSUЄ-07-2-3, cephalon exposing ventral sclerites; CSUЄ-07-2-4, partial late-stage meraspis missing pygidium; CSUЄ-07-2-7, CSUЄ-07-2-8, pygidia.

Occurrence—Locality 1, Murray County, Georgia.

Diagnosis—Ptychopariina with co-equal preglabellar field and border, librigenae separated by a narrow rostral plate, natant hypostome clearly detached skeletally from the doublure, short preglabellar field with indistinct border furrow; short, stout genal spines reaching posteriorly no farther than the second thoracic segment and laterally extending from the thorax at relatively large angles. Pygidia relatively wider (tr.) than long, with three poorly demarcated axial rings plus indistinct posteroaxis.

Discussion—This *Aphelaspis* species is extraordinarily abundant in Locality 1 and commonly preserved with intact librigenae and found in a wide variety of size classes, including meraspides. Many species of *Aphelaspis* have been recognized, many of which are dubious: over-splitting of the genus is evident in various literature sources: for example, Rasetti (1965) recognized fifteen species of *Aphelaspis* in Tennessee, including eleven of which he erected in that single publication. Among the many (and variable) described species of *Aphelaspis*, the broad, strongly divergent spines combined with the short, indistinctly segmented pygidium closely conform with the type specimens from Nevada in Palmer (1962), as well as material tentatively referred in Pratt (1992). The specimens from the Conasauga Formation are flattened but complete, and therefore some

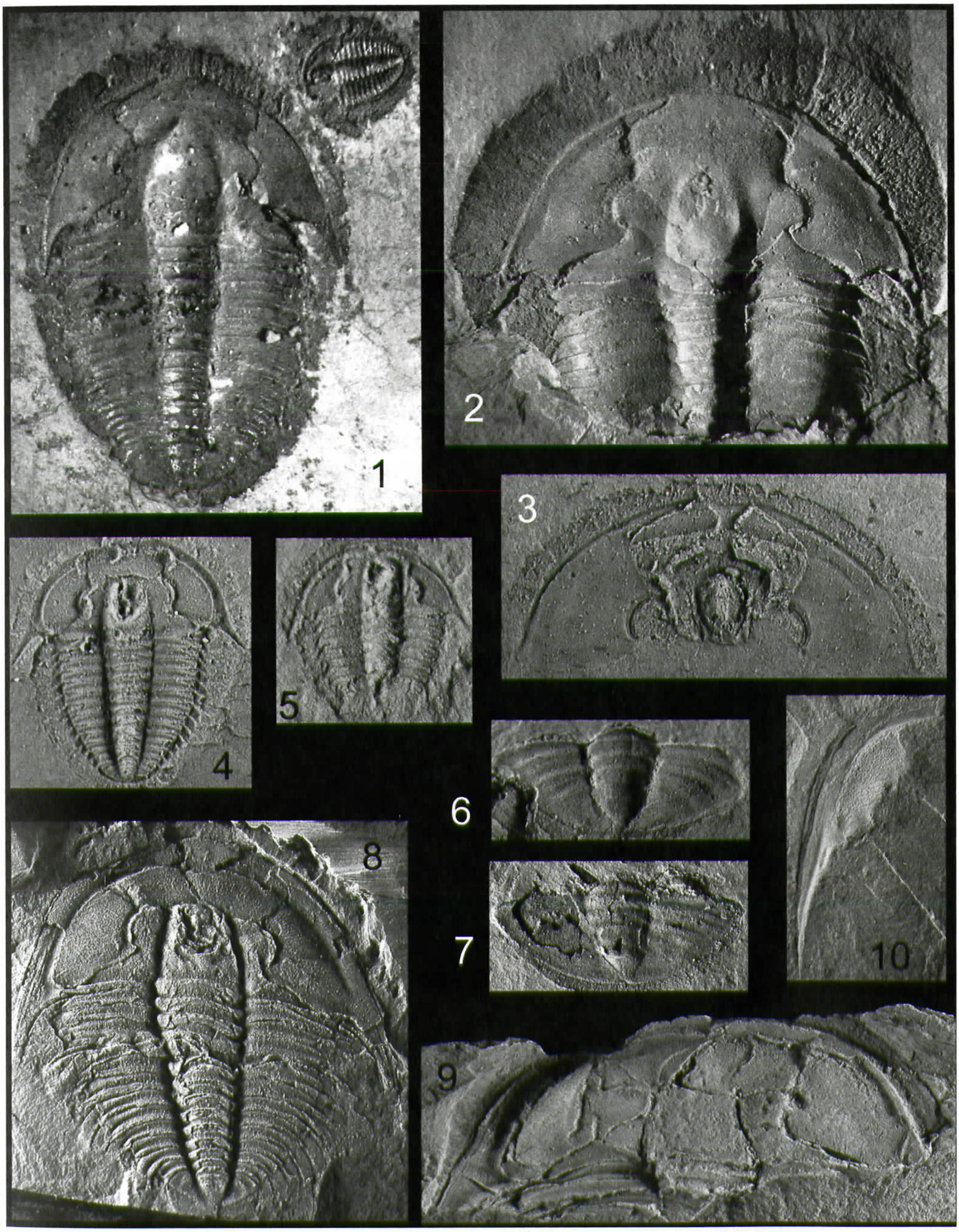

Figure 3—Ptychopariine trilobites from Localities 1 and 2. *1-7*, *Aphelaspis brachyphasis* Palmer, from Locality 1; *1, 2*, larger holaspides with attached librigenae, showing iron-oxide halos; *1*, CSU€-07-2-1, *2*, CSU€-O7-5-6, both x5.5; *3*, ventral view of cephalon, showing labrum and rostral plate, CSU€-07-2-3, x7.5; *4*, small holaspis with attached librigenae, CSU€-07-5-5, x5; *5*, partial meraspis, CSU€-07-2-4, x10; *6,7*, pygidia; *6*, CSU€-07-2-7, x3.5; *7*, CSU€-07-2-8, x5. *8-10*, *Eugonocare (Olenaspella) separatum* (Palmer), from Locality 2; *8*, holaspis with intact librigenae, CSU€-07-3-1, x3.5; *9*, cephalon and anterior thorax of larger individual, CSU€-07-3-5; *10*, isolated librigena, CSU€-07-3-6, both x2.

features comparable with the holotype may be exaggerated or distorted, such as the lateral spread of the genal spines and the width of the pygidium. This is the first occurrence of this species in the eastern continent.

Genus *Eugonocare* Whitehouse, 1939
Eugonocare (Olenaspella) separatum (Palmer, 1962)
Figures 3.8-3.10

Referred Material—CSUC-07-3-1, complete holaspis; CSUC-07-3-4, larger cephalon and partial thorax; CSUC-07-3-5, isolated librigena.

Occurrence—Locality 2, Gordon County, Georgia.

Diagnosis—Aphelaspinae with transversely wide cranidia, equally wide librigenae with broad margin, wide, deep, marginal furrow. Preglabellar field long (sag.), slightly inflated, with fine radiating striations. Genal spines long and broad, reaching posteriorly to the sixth thoracic segment. Thoracic segments with deep interpleural furrows, terminating in relatively long marginal spines. Pygidium relatively small with five segments and a single pair of marginal spines on the anterior segment.

Discussion—The specimens here retain the librigenae, showing the proportionately large size of the cephala. However, the preservation of some individuals incorporates distortion of the claystone matrix (e.g. Figure 3.9), skewing the body proportions. Most generic and specific descriptions of *Eugonocare* sp. are based on isolated cranidia, free cheeks and pygidia, and complete individuals such as figured here are relatively rare. It is therefore notable that the thorax shows segments with deep interpleural furrows and elongate marginal spines. The marginal spines, in particular, are confluent with the diagnostically spinose morphology of the anterior pygidium. Identification of *Eugonocare separatum* in the Conasauga Formation further extends the geographic range to eastern North America. Peng (1992) recognized three subgenera of *Eugonocare*, including *Eugonocare* (*Olenaspella*), which in his concept comprises a distinct North American subgenus. The specimens discussed here clearly conform to that morphology, whether or not the subgeneric classification is necessary.

TAPHONOMY AND BIOGEOGRAPHY

Preservation of Complete *Aphelaspis* and *Eugonocare*

Specimens of *Aphelaspis* and *Eugonocare* from both localities contain a majority of individuals with intact librigenae (see, for example, Figures 3.1-3.4, 3.8, 3.9). Such fossils represent dead trilobites rather than molted exuviae, since the librigenae of ptychopariines were typically separated during exuviation along the facial sutures (Whittington, 1997b), and are almost always found in molts separated from the cranidia. At locality 1 complete *Aphelaspis* individuals are very abundant and frequently occur as multiples, sometimes overlapping, within decimeter-scale slabs. Such occurrences are termed "body clusters" in Whittington, 1997b, and represent death assemblages (versus "molt clusters" representing marine current sorted exuviae accumulations). Given the abundance of apparently dead individuals, combined with the well sorted, fine-grained enclosing lithology, it is inferred that the *Aphelaspis* specimens here were killed and preserved by episodes of rapid immuration in mudflows, most likely on the outer marine shelf or a deeper marine basin environment.

It is also significant that many of the complete (thus dead) specimens are surrounded by iron oxide (goethite) halos (see, e.g., Figure 2.1). These oxides are the final event in a preservational-depositional sequence (Schwimmer and Montante, 2007) which begins with precipitation of pyrite around the decaying organism (Borkow and Babcock, 2003; Popa and others, 2004). Pyrite is commonly precipitated when decay gases cause locally reducing conditions in iron and sulfur-rich marine waters, which subsequently oxidizes to ferrous oxides when the sediment is exposed at any later time to higher oxygenated groundwater or subaerial environments. In addition to authigenic sulfide deposition, we infer there was locally low oxygen conditions in the Conasauga Formation based on the near absence of burrow traces in the Conasauga Valley mudstones containing the complete *Aphelaspis* specimens: the absence of significant infaunal traces implies low oxygen conditions especially below the sediment-water interface.

Similar pyrite deposition and goethite replacement around intact trilobite specimens was reported in nearby late Middle Cambrian trilobite assemblages (*Bolaspidella* Zone) in the Coosa Valley in Georgia (Schwimmer and Montante, 2007). In both the latter and present situations, the mode of trilobite preservation (intact librigenae and oxides halos) apparently resulted from the combination of relatively low-oxygen conditions below the sediment-water interface, and well-sorted mud sedimentation on the outer marine shelf. These similar marine conditions, found in two closely-spaced trilobite chronozones (*Bolaspidella* and *Aphelaspis* Zones) suggest that stable marine conditions persisted on the extreme southwestern continental shelf-edge.

Paleobiogeography

The Conasauga River Valley localities discussed here are the southeastern most exposures of Upper Cambrian strata in the southern Appalachian region. The nearest Upper Cambrian trilobite faunal locality (which correlates very well biostratigraphically with the Conasauga Valley localities) is at Cedar Bluff, Alabama, in the Coosa River Valley (Palmer, 1962; Butts, 1926), located approximately 75 km to the west. The palinspastically reconstructed distance between these localities was substantially greater in the Cambrian, and also involves some clockwise rotation (Thomas and Bayona, 2005) since there are several transform detachments and thrust fault zones intervening between the localities. The Late Cambrian separation between these *Aphelaspis* faunal sites reconstructs to approximately 145 km on the Cambrian marine shelf.

It is noteworthy in this context that the respective Cedar Bluff, Alabama, and Conasauga Valley, Georgia, assemblages have identical agnostoids, but that the abundant *Aphelaspis brachyphasis* of the Conasauga Valley were not reported at Cedar Bluff (Palmer, 1962). The muddy, low-oxygen sedimentary and taphonomic conditions inferred for the Conasauga Valley localities, suggest that these deposits accumulated on the distal edge of the shelf or in a relatively deep intrashelf basin. In contrast, Palmer (1962) reported the strata at Cedar Bluff, Alabama (located northwestward, toward the mid-continent) to be composed of interbedded shales and thin-bedded limestones. This slight sedimentary and faunal change from west (Cedar Bluff, Alabama) to east (Conasauga Valley), may reflect the paleotopographic break (Thomas and others, 2000) from the Alabama Promontory shelf edge (then, due northwest) across the transform to deeper water in the Tennessee Embayment (then, to the southeast). Carrying this argument one step further, we may also infer that the species *Aphelapsis brachyphasis*, which was apparently absent at Cedar Bluff, may have been endemic to the deeper, basinal marine environment represented in the Conasauga Valley localities.

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A NEW GENUS AND SPECIES OF ECHINOID (ECHINOIDEA, SPATANGOIDA) FROM THE OLIGOCENE (RUPELIAN) OF MISSISSIPPI

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ABSTRACT

A new genus and species of spatangoid echinoid, *Tripatagus pittsi* n. gen., n. sp., is described from the Marianna Limestone, Lower Oligocene (Rupelian) of Mississippi. The family is uncertain: plating of the plastron suggests the family Maretiidae; ethmolytic apical system, presence of both peripetalous and subanal fascioles, and depressed petals suggest the family Brissidae or Macropneustidae. It differs from nearly all other genera of these families in the character of 3 gonopores in an ethmolytic apical system, lacking a gonopore in genital plate 2.

INTRODUCTION

The holotype of *Tripatagus pittsi* n. gen., n. sp. was collected *in situ* from exposed Marianna Limestone in a quarry near Sylvarena, Smith County, Mississippi. Additional specimens were found in the collections of the Mississippi Museum of Natural Science, Jackson. Specimen labels indicated that the latter specimens were collected from one of the pits at the Marquette Cement Company quarry site at Brandon, Rankin County, Mississippi, probably in the 1960's. When these pits were active quarry operations exposed the Bucatunna, Byram, Glendon, and Marianna Formations, with a thin section of Mint Spring Member of the Marianna penetrated below water level in the original pit. All of these formations are included within the Vicksburg Group of the Gulf Coast Oligocene.

GEOLOGIC SETTING

The stratigraphic nomenclature described by Mancini and Tew (1991) for central Mississippi is followed here (Figure 1). The geologic section at the Marquette site was diagrammed in a University of Southwestern Louisiana Geological Society guidebook (USL Geological Society, 1965), and Dockery (1982) published some photographs of the quarry when it was active. At the base of the section is 2 meters of Marianna Limestone, the lower ½ meter of which is the

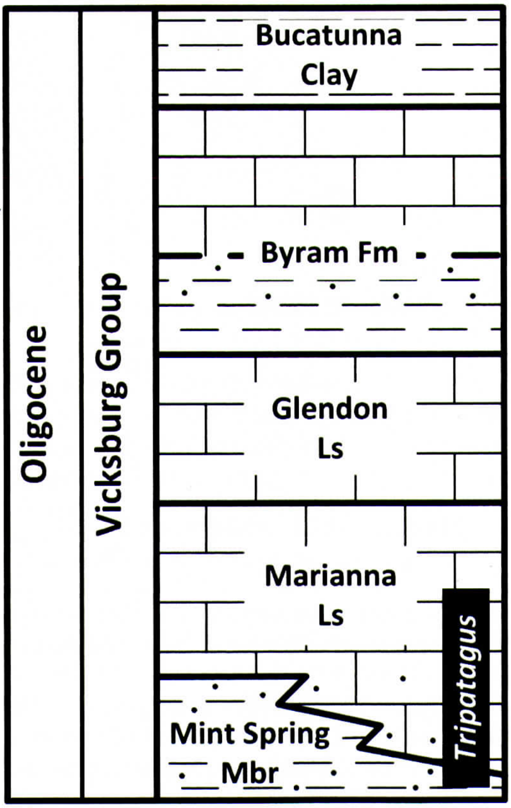

Figure 1. Stratigraphic column for Vicksburg Group, central Mississippi. Estimated stratigraphic occurrence of *Tripatagus pittsi* n. sp. is indicated by the dark vertical bar.

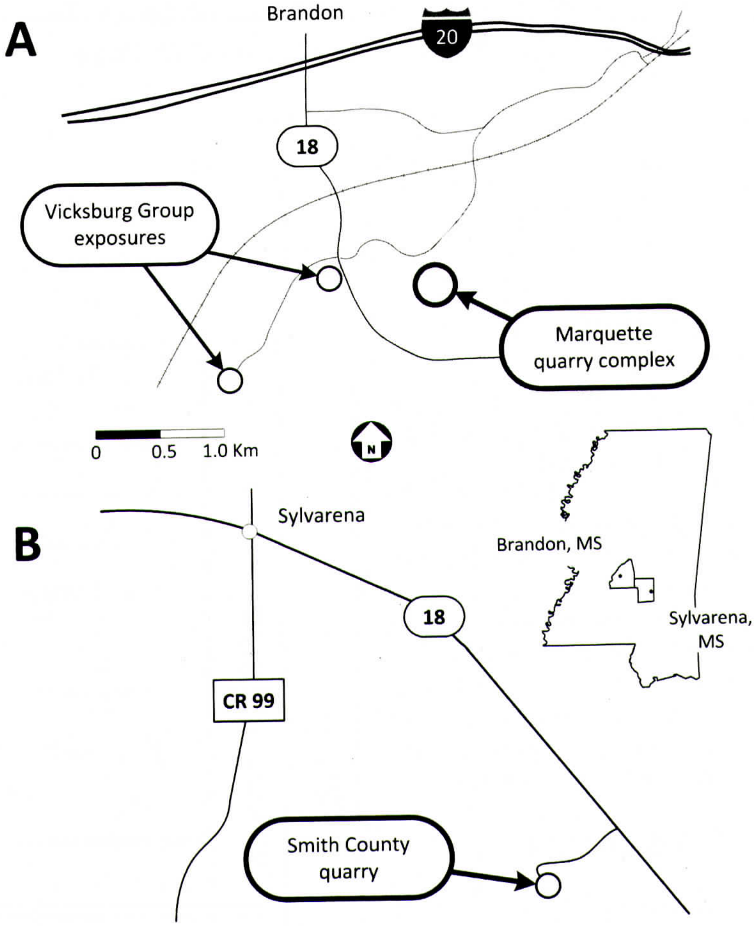

Figure 2. Location map. A, Marquette quarry complex is indicated by the large circle, alternate collection areas by smaller circles. B, Smith quarry (type locality).

Mint Spring Member (below water level). This is overlain by 1 meter of Glendon Limestone, and 4 meters of shale and limestone of the Byram Formation. The section is capped with a thin clay unit attributed to the Bucatunna. The quarry area is now heavily overgrown and water-filled, with scattered, poor exposures of the upper section. More recent excavations 1 to 2 kilometers west of the Marquette pits offer better exposures of the Mint Spring through Glendon section where the new species occurs (Figure 2). The Mint Spring Member at these locations is fossiliferous, soft, arenaceous marl. This lithology grades upward into typical Marianna Limestone, a more compact, fine-grained, clayey limestone, interbedded with coarser, bioclastic units. The Marianna section is capped by hard, sparsely fossiliferous limestone of the Glendon Member of the Byram Formation. The Marianna section is characterized by abundant large, benthic foraminifera *Lepidocylina mantelli*, the bivalve *Pecten poulsoni*, and echinoids, including *Clypeaster rogersi*, *Rhyncholampas gouldii*, *Schizaster americanus*, and *Agassizia* sp.

The lithology of sediments preserved inside the Marquette *Tripatagus pittsi* specimens ranges from a very fine-grained limestone with scattered grains of glauconite and very few quartz grains, to a bioclastic grainstone made up of fragments of echinoid spines, mollusks, bryozoans, and foraminifera. The finer-grained material is indistinguishable from that characterizing the Marianna Limestone, with

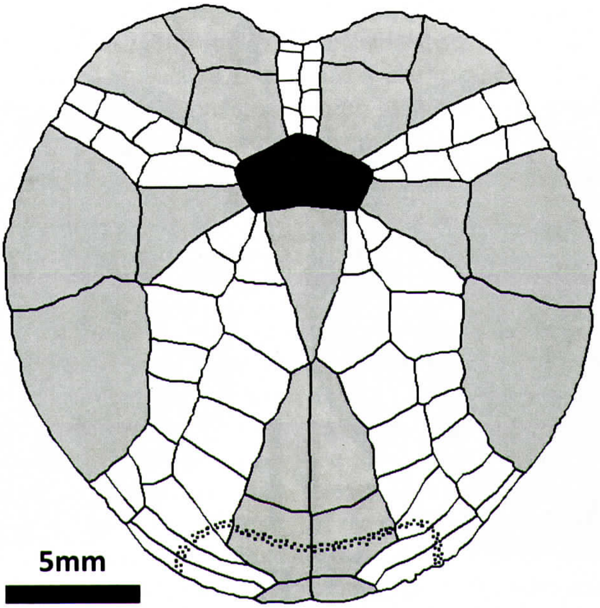

Figure 3. Adoral plating of *Tripatgus pittsi*, n. gen., n. sp., holotype, MMNS IP-4006.

the bioclastic material suggesting the lower part of the section where it grades into the Mint Spring Member. The source of the Marquette specimens is most likely from the lower section of Marianna Limestone. The Smith County specimen (holotype) was collected directly from the Marianna Limestone.

The Marianna Limestone was deposited on a relatively deep (actual depth unknown) carbonate shelf (Pettway and Dunn, 1990) during a period of global ocean cooling (Zachos et al., 2001).

SYSTEMATIC PALEONTOLOGY

Type and figured specimens of *Tripatagus pittsi* n. gen., n. sp. are held by the Mississippi Museum of Natural Science (MMNS) at 2148 Riverside Drive, Jackson.

Class Echinoidea
Order Spatangoida
Infraorder Micrasterina
Family Uncertain
Tripatagus, new genus

Type species— *Tripatagus pittsi,* n. sp. by monotypy.

Diagnosis— As for type species.

Etymology— Incorporates the prefix tri- with the root –patagus to indicate the 3 gonopores. The gender is masculine.

Tripatagus pittsi, new species (Figure 3; Figure 4, A-G)

Diagnosis— Test small, cordate. Apical system ethmolytic, 3 gonopores, no gonopore in genital plate 2. Anterior ambulacrum non-petaloid, slightly sunken, pores uniserial; petals more deeply and broadly sunken, straight, anterior and posterior nearly equal length, pores non-conjugate, occluded plate at terminus of posterior petals. Sparse, scattered, perforate, non-scrobiculate primary tubercles. Peristome pentagonal, slight posterior lip, labrum elongate, plastron amphisternous. Peripetalous fasciole present anteriorly, indented. Subanal fasciole bilobed.

Description— Test small (length 30mm or less), cordate, outline equant to slightly wider than long; relatively low, maximum height at apical system; modest anterior sulcus most apparent at margin. Apical disk anteriorly eccentric (40% of test length from anterior margin),

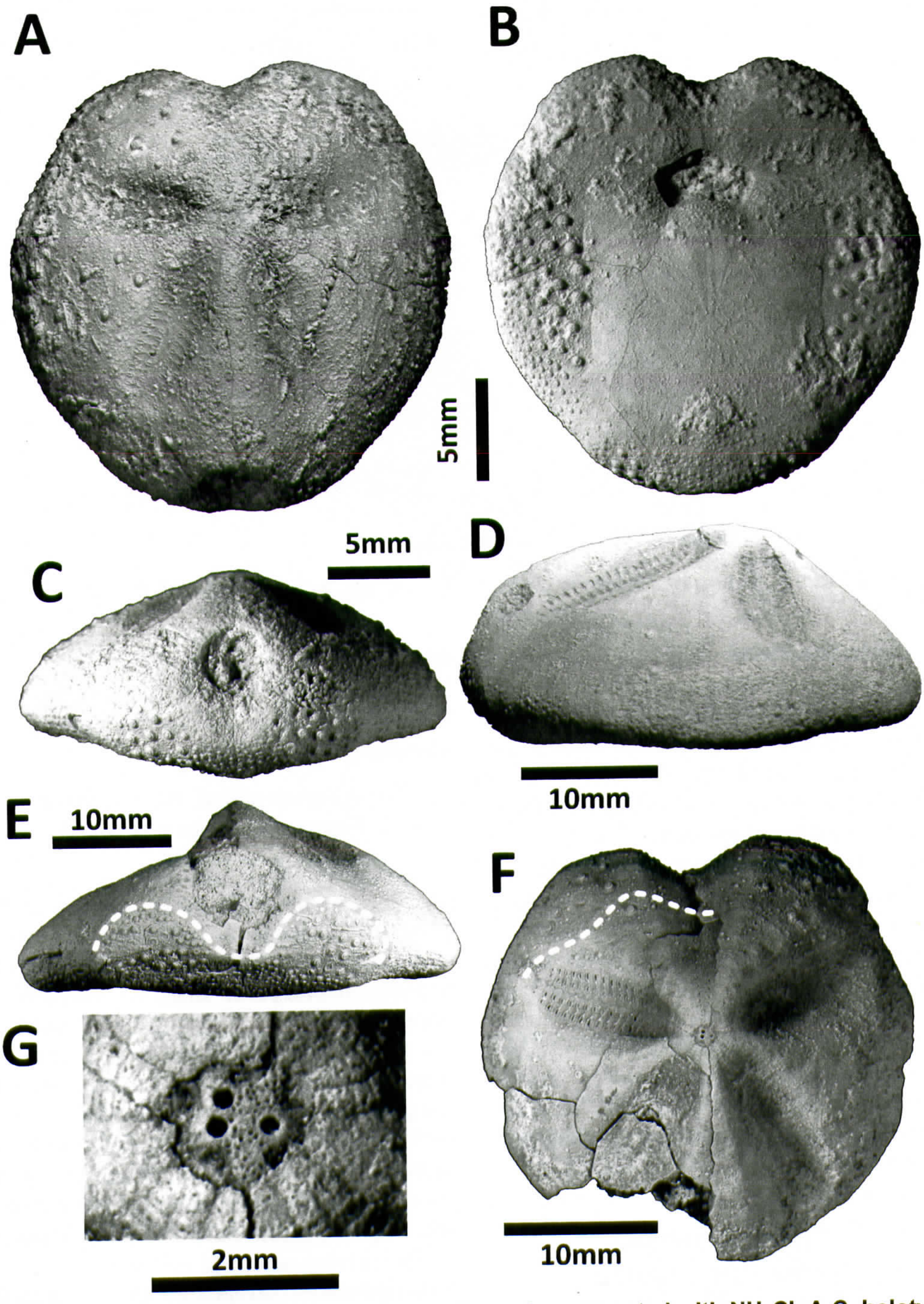

Figure 4. *Tripatagus pittsi*, n. gen., n. sp. All specimens coated with NH_4Cl. A-C, holotype, MMNS IP-4006, aboral, oral and posterior views; D-E, Paratype, MMNS IP-3929, right lateral view; E, posterior view, trace of subanal fasciole outlined; F-G, paratype, MMNS IP-103.1, F, aboral, trace of peripetalous fasciole outlined; G, apical system.

ethmolytic, 3 gonopores, no gonopore in genital plate 2. Anterior ambulacrum slightly sunken, pores small, uniserial; paired ambulacra petaloid, deeply sunken, straight, anterior and posterior nearly equal length, anterior petals about 40% of test length, posterior about 46%, final plate in petals occluded. Pores non-conjugate, outer pore more elongate than inner, interporiferous areas naked. As many as twelve primary perforate, non-scrobiculate tubercles with shallow, symmetric areolae in aboral interambulacra 2 and 3, as many as five or six in interambulacra 1 and 4. Number of primaries varies inversely with test length, circular scars record loss of primary tubercles on larger specimens. Indented peripetalous fasciole only known for certain from anterior of test. Periproct terminal, taller than wide, set at top of short, slightly indented posterior face, two areas of 5-6 primary perforate, non-scrobiculate tubercles on either side below the periproct, enclosed within bilobed subanal fasciole. Peristome distinctly pentagonal in holotype, semi-pentagonal in paratypes, with very slight posterior lip, phyllodes very poorly developed, no floscelle. Plastron amphisternous, labrum broad and elongate, about 25% of test length, extends nearly to third ambulacral plate, projects between sternal plates, tuberculate only near lip. Plastron and periplastron mostly naked, sternal plates tuberculate only on posterior half. All adoral interambulacra amphiplacous. Primary perforate, scrobiculate tubercles with shallow, asymmetric areolae in adoral interambulacra 1 and 4, adoral ambulacra I and V naked.

Etymology— The specific name honors the collectors Leslie and Sue Pitts.

Material— Holotype MMNS IP-4006 (length (L) 22mm, width (W) 21.5mm, height (H) 9mm. Four paratypes, MMNS IP-3929 (L 30mm, W 30.5mm, H 12.5mm), MMNS IP103.1 (L ~26mm, W 27mm, H 9mm), MMNS IP103.2 (L 30mm, W 31mm, H 12mm), and MMNS IP-103.3 (L 27mm, W 28mm, H 10mm).

Occurrence— Smith County Lime Plant quarry, west of State Highway 18, 3 kilometers southeast of Sylvarena, 31° 59' 24" N, 89° 21' 37" W (holotype; George Phillips, collector). Abandoned pits at Marquette Cement Company quarry site east of State Hwy 18 about 1.6 km south of Interstate 20, Brandon, Mississippi. The group of pits is centered near 32° 15' 45" N, 90° 01' 30" W (paratypes; Leslie and Sue Pitts, collectors). Marianna Limestone, Vicksburg Group, Oligocene (Rupelian).

Discussion— Circular scars representing loss of primary tubercles on the aboral surface are more common on larger specimens and were probably caused by ontogenetically controlled autotomy (David and Neraudeau, 1989). The test surface is worn in all specimens, revealing the fine mesh-work of stereom microstructure preserved in various areas on the test. This loss of the outermost surface of the skeleton makes it particularly difficult to delineate fascioles and other fine surface tuberculation. The peripetalous fasciole can be seen anteriorly on 2 of the paratypes (MMNS I-3929 and I-103.1), but the fine tuberculation of the subanal fasciole can only be seen on one of these (MMNS I-3929). The character of 3 gonopores in the apical system is known from only one other spatangoid species from the Cenozoic of the southeastern United States, *Cyclaster drewyensis*, described by Cooke (1942) from the Oligocene of Alabama. The apical system of *C. drewyensis*, however, is ethmophract rather than ethmolytic.

Based on the most current system of classification (Kroh and Smith, 2010), the family is uncertain: plating of the plastron and oral ambulacra suggests the family Maretiidae; ethmolytic apical system, presence of both peripetalous and subanal fascioles, and depressed petals suggest the family Brissidae or Macropneustidae. Four maretiid genera have 3 gonopores, *Hemimaretia*, *Pseudomaretia*, *Nacospatangus*, and *Goniomaretia*. None of these have a peripetalous fasciole. The presence of 3 gonopores is known in one brissid, *Anabrissus,* which differs by having the gonopore missing from genital plate 3 rather than 2. The macropneustid *Archaechinus* is similar, with 3 gonopores in an ethmolytic apical system and bilobed subanal fasciole, but differs in adoral plate structure, lack of a strong anterior sulcus, and flush petals. All other genera with 3 gonopores differ in number and type of fascioles, ethmophract rather than ethmolytic apical systems, or genital plate other than G2 lacking the gonopore. Lambert (1933) described the species *Plesiopatagus hourcqi* which has 3 gonopores in the correct position, but the genus *Plesiopatagus* was shown by Gauthier (1899) to have only 2 gonopores, both on the left side of the apical system. The type and only known specimen of *P. hourcqi* is badly crushed and although the published figure indicates that it shares similarities with *T. pittsi*, the species is only incompletely known and itself of uncertain generic affinity.

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